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HYDRAULIC RAM EFFECTS IN LIQUID PROPELLANTS

Robert White
Luis Vargas
Southwest Research Institute

William O. Seals

September 1988

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

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Preliminary vulnerability tests with liquid propellant stored in one gallon plastic and steel containers resulted in very high hydraulic-ram pressures when containers were impacted by shaped charges. These pressure and attending mechanical shock and vibration exceeded the limitation of the Kistler pressure transducers used in these pressure measurements. Since liquid propellants will be stored in larger volumes in armored vehicles, it is imperative to have a means of predicting the high pressures and impulse. The measurements are critical to the design of liquid propellant storage containers that will properly vent the high pressures and ensure maximum safety to immediate personnel. Small-scale tests were conducted that will be used to predict the hydraulic-ram effects in larger, stored liquid propellant quantities. This paper will address the development of a model that can predict the effect produced by liquid propellants when a high energy source produces hydraulic-ram in a heavily confined container.

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INTRODUCTION

The use of liquid propellants in a large caliber gun system has been under evaluation by the U.S. Army. Liquid propellant systems present many advantages as a replacement for solid propellants in selected applications. However, there are hazards involved with all propellants whether in the manufacturing, handling, storage, or application. The sensitivity of propellants to external stimuli is of extreme importance. In the battlefield role, it is imperative that propellant sensitivities to external stimuli such as projectile or shaped charge impact be known. This program was designed to determine the vulnerability of liquid propellant containers to simulated shaped charge impact.

BACKGROUND

Preliminary tests have shown that very intense hydraulic ram pressures and widespread fluid spills occur when small scaled liquid propellant containers are impacted by shaped charges or when they are subjected to energy discharges created by the detonation of high explosives within the containers. Several tests were performed by shooting a shaped charge through 1-gal. polyethylene containers; shock pressures in excess of 100,000 lb/in.^{2} were reported. These tests resulted in destruction of both the containers and the pressure transducers. The importance of the degree of confinement and quantity of materials has not previously been addressed and this program was developed to provide information in these areas. The major goals were to perform hydraulic ram tests on scaled, cylindrical, liquid-propellant containers varying both the input energy and the volume and then use the data generated to develop a physical, mathematical model for predicting pressures that could be developed from external battlefield threats to stored, liquid propellants.

TESTING

Container Fabrication

Southwest Research Institute (SwRI) fabricated liquid propellant test canisters using 304 stainless steel tubes in three diameters (3.5, 4.0, and 6 in.). Sections of the tubes were cut to the appropriate length to yield volumes of a pint, a quart, and a half-gallon, respectively, and were welded to an 8-in.^{2} stainless steel base plate on-half in. thick. Stainless steel witness plate, the same size as the base plates, were also fabricated for use in the test program. These plates are referred to as "light" plates, each weighs 9.15 lb. Another weight witness plate, 2-in. thick (designated as "heavy" plate, weight of 18.3 lb) was used during some of the preliminary tests to compare with light plate results. The heavy plate was not employed for the proof-test experiments.

The baseplates were originally drilled and tapped to accept PCB Model 109A02 pressure transducers for use in measuring the transient pressure within the fluid. However, subsequent tests proved that the transducer would have to be mechanically isolated from the canister to reduce shock and vibration to the transducer amplifier circuit inside the transducer body.

Test Program

The hydraulic ram testing was conducted at the SwRI Ballistics Range. Three explosive charge energy levels were used and both water and NOS 365 liquid propellant were employed as test fluids. Electric bridge wire detonators (RP 83), commercial blasting caps (No. 8), and No. eights attached to short lengths of prima cord were used to impart the energy to the fluids in the canisters to produce the simulated shape charge hydraulic ram. The detonators and prima cord charges were inserted into the canisters from the top and were centered in the canister. The witness plate was then placed on top of the canister and the charge was detonated. The test procedure called for measuing the shock and drag phase of the canister internal pressure and for measuring the height that the witness plare was launched by the dynamic forces. Witness plate velocities were measured by breakwire electronic circuits and by calculations based on video camera recording observations. Video camera coverage was also provided for measuring the height that the witness plare traveled. A 8-ft high gridded background was prepared for use in the height measurements from video recordings and a 20-ft high ruled pole was positioned next to the background for tests where the witness plate went more than 8 ft high. A total of 22 preliminary tests followed by 18 proof tests were performed using the three container sizes.

Initially, tests were conducted with the piezoelectric pressure transducers mounted directly to the canister baseplate. These tests often resulted in severe shock/vibration-caused damage to the transducer and loss of the pressure-time histories. Several "fixes" were incorporated and tested in an attempt to reduce the vibration related loads that were believed to be damaging the pressure transducers. Subsequently, test yielded information indicating that the transducers were indeed being damaged by shock loading and not by overpressures or by compressive side loads. A scheme was developed to shock isolate the transducer and was successfully demonstrated. This scheme involved mounting the pressure transducer within a thick concrete pad (fig. 1). A 1-in. steel plate was bolted to the concrete pad. The canister baseplate was, in turn, bolted to the steel plate. Both the 1-in. steel plate and the canister baseplate had a slightly oversized hole machined into them to permit the transducer to mount flush with the inside of the canister baseplate. The void around the transducer was filled with an RTV potting material which would prevent leakage of the liquid propellant and would also isolate the transducer from any metal contact with the canister baseplate. Photographs of a typical test setup and also a view into the canister where the "potted" transducer is visible are shown in figure 2.

Summaries of the tests performed including the preliminary tests are given in tables 1 and 2; witness plate launch heights and maximum pressure in table 1 and witness plate velocities in table 2. The following section presents short summaries of each of the tests conducted.

Preliminary Tests

Test No. 1. This test employed a 1/2 gal canister filled with water. A single RP 83 detonator having a total explosived weight of 16 grains was used. The test was conducted using a light witness plare (8 in. x 8 in. x 1/2 in.) which was launched to a height of 20.5 feet. For this test, the witness plate velocity as measured from video tape recording was 40 ft/s at the 1-ft height. The analysis of the pressure data did not yield any usable data. High intensity shock and vibration loads in the fixture damaged the transducer's internal amplifier. The canister suffered minor damage consisting primarily of some bluding in the sides of the canister. The damaged transducer was discarded.

Test No. 2. This test employed a 1/2 gal. canister filled with water. An RP 83 detonator and a 2.4 in. section of 80 grain per foot prima cord provided a combined total explosive weight of 32 grains. The test was conducted with the light witness plate and the plate was launched to a height in excess of 64 feet. For this test, the witness plate velocity as measured from video tape recroding was 66.7 ft/s at the 2-ft height. The canister suffered major bulging in the sidewalls but no other major damage. The pressure recording for this test was evaluated and found to contain several higher frequency data that were coupling over the pressure data making it impossible to determine actual pressures. It was felt that these extaneous signals were probably being caused by side loading of the transducer. The transducer was damaged internally and was discarded.

Test No. 3 This test was performed using liquid propellant in the 1/2 gal. container and was initiated using a single RP 83 EBWS detonator and the light (1/2 in. thick) witness plate. For this test, the pressure transducer was "potted" using an RTV material to eliminate any side loads. The test launched the witness plate to a height of approximately 27 ft and the canister suffered slight dmage consisting of bulging in the sidewalls. For this test, the witness plate velocity as measured for video tape recording was 42.9 ft/s at the 2-ft height. There was no evidence of any kind of reaction or ignition by the liquid propellant. The analysis of the pressure trace again showed the coupling of extraneous responses over the pressure data making the determination of actual pressure impossible. The transducer was damaged internally and had to be discarded. It appears that the transducer was still experiencing side loads, and a review of the video showed that the canister baseplate appeared to be rebounding upward and flexing from the dynamic loads. It was decided to try and isolate the pressure transducer by enlarging the cavity well surrounding the diaphragm end in the baseplate

so that any plate flexure would not be directly in contact with the transducer body. In addition, the test canister was rigidly attached to massive steel support plate in order to try and dampen the response of the base plate.

Test No. 4. This test was conducted using another 1/2 gal. container filled with liquid propellant and with a smaller detonator, a no. 8 commercial blasting cap that contains approximately 8 grains of explosive. This test also used the heavier (1.0-in. thick) witness plate and with the pressure transducer mounted in the larger cavity. The cap was initiated and the witness plate flew 9.5 feet. For this test, the witness plate velocity as measured from video tape recording was 22.2 ft/s at the 2-ft height. The canister suffered minor damage consisting of slight bulging in the sidewalls. However, the analysis of the pressure data again showed coupling of extraneous signals and subsequent evaluations indicated that the transducer was picking up the canister vibrations induced by the blast. The "ringing" of the canister and baseplate was being picked up by the transducer and was being coupled with the pressure signals. It was decided that in the next test the transducer should be completely isolated from the baseplate which could be accomplished by inserting the transducer inside of a nylon bushing which would then be threaded into the canister baseplate.

Test No. 5. This test was conducted with a 1/2 gal. canister and a no. 8 cap. Water was used. The pressure transducer was isolated from the baseplate in a nylon bushing. The no. 8 detonator was initiated and the witness plate was launched 5.75 feet. For this test, the witness plate velocity as measured from video tape recording was 20 ft/s at the 1-ft height. The blast loads sheared the threads on the nylon bushing and the transducer was blown out the baseplate. The transducer was recovered on the ground and found to be unharmed. A review of the pressure data recording showed a maximum dynamic pressure of 30,000 lb/in.^{2}

Test No. 6. This test used a 1-qt container full of water and the small detonator (8 grains of explosives). The 1-in. thick witness plate was used on this test and pressure transducer was isolated from the baseplate with a "stand-off" tube. One end of the tube was threaded into baseplate while the other end connected to a conversion fitting, a Swagelok coupling, and a fitting into which the pressure transducer was threaded. The tube transmitted dynamic pressures to the transducer and at the same time prevented the transducer from sensing mechanical vibrations. The detonator was fired and the witness plate was launched to a height of 2.6 feet. For this test, the witness plare velocity as measured from video tape recording was 12.5 ft/s at the 1-ft height. The pressure transducer signal measured corresponded to a maximum dynamic pressure of 8,000 lb/in^2. The canister suffered minor damages again consisting of a deformation of the sidewalls through plastic deformation

Test No. 7. This test was conducted on a 1/2 gal. container filled with water and using a no. 8 detonator cap. The pressure transducer was mounted using the stand-off tube as was done in the previous test. The initiator was fired and the

1.0-in. thick witness plate lid was launched approximately 7 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The transducer peak pressure signal measured approximately 7,100 lb/in.^{2}

Test No. 8. This test was performed using a 1/2-gal. canister filled with water. A single no. 8 detonator having an equivalent HMX explosive weight of 7.78 grains was employed. The test was conducted using a heavy witness plate (8 in. x 8 in. x 1 in.) which was launched to a height of 6.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. This test used two pressure transducers. The first transducer (no. 1) was installed in a nylon insert which in turn was screwed directly into the canister baseplate; the second (No. 2) was installed in an offset tube arrangement consisting of a fitting housing the transducer, a stainless steel tube segment, and a Swagelok connector, and the tube was threaded at the other end and attac ,ed directly to the canister baseplate. The purpose of the stand-off arrangement was to isolate the transducer from the plate. The anlysis of the pressure data showed that the transducer in the nylon insert directly attached to the canister measured an initial maximum peak pressure of 19,840 lb/in.^{2} and transducer no. 2 (in the stand-off tube) measured an initial maximum peak pressure of 5,780 lb/in.^{2}. The pressure measured by transducer no. 2 was attenuated by the stand-off tube arrangement. Both transducers appeared to survive the test undamaged, and were installed for the next test. The canister suffered minor damage consisting primarily of some bulging in the sides of the canister.

Test No. 9. This test was a repeat of the previous test and employed a 1/2-gal. canister filled with water and tested with a no.8 detonator. The test was conducted with the 1-in. thick witness plare and with the two transudcers, one in the nylon insert and the other in the stand-off tube arrangement. The witness plate was launched to a hieght of 6 ft and the canister suffered major bulding in the sidewalls but no other major damage. For this test, the witness plate velocity as measured from a video tpe recroding was 20 ft/s at the 1-ft height. The pressure recordings for this test were evaluated and the transudcer in the nylon insert gave measured data with an initial peak pressure of approximately 24,300 lb/in.^{2} and a maximum pressure of 31,470 lb/in.^{2}. The second transducer in the stand-off tube measured a maximum of 4,880 lb/in.^{2} which again appeared to be significantly attenuated. Post-test inspection revealed that the nylon insert had failed and the transducer and a portion of the insert had been blown out of the canister mounting by the shock load. It was decided that the stand-off tube arrangement was causing significant attentuation of the pressure signals and was not to be used in subsequent tests. The "insert" technique appeared to work adequately; however, it was decided to use a stronger type of insert to withstand more of the shock and vibration loads than the nylon insert was able to withstand.

Test No. 10. This test was performed using a quart container filled with water and was initiated by detonating a single no. 8 EBW detonator. The light (1/2-in.

thick) witness plate used for this test and the pressure transducer was installed in a metal fitting which, in turn, was isolated from the canister baseplate using a nylon bushing. The test launched the witness plate to a height of approximately 6.3 ft and the canister suffered slight damage consisting of bulging in the sidewalls. For this test, the witness plate velocity as measured from a video tape recording was 16.7 ft/s at the 1-ft height. The analysis of the pressure trace showed a maximum peak pressure of 24,370 lb/in.^{2}.

Test No. 11. This test was a repeat of the previous test and used a quart filled with water, a no. 8 detonator, and the light witness plate. The detonator was initiated and the witness plate flew 7.0 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The canister suffered minor damage consisting of slight bulging in the sidewalls. The analysis of the pressure data revealed a maximum initial peak pressure of 21,000 lb/in.^{2} and also revealed that the transducer was severely damaged during the test. Only the peak initial pressure data appear to be usable. It was decided that in the next test the transducer should be completely isolated from the baseplate which could be accomplished by mounting the transducer on a separate plate, drilling a penetration in the canister baseplate, placing the canister over the transducer, and potting it with RTV to provide a seal

Test No. 12. This test was a repeat of the quarter test with the transducer mounted in a separate plate and the canister placed over the transducer. A no. 8 cap was used as was the light witness plate. The no. 8 detonator was initiated and the witness plate was launched 5.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The pressure transducer data indicated a maximum peak initial pressure of 26,000 lb/in.^{2} but once again, the press -e trace indicated that the transducer had been damaged and that the peak initial pressure data were the only usable data. A test was conducted to determine the accelerations being generated in order to see if the transducers were being damaged by shock loading or by side loads. The test was conducted using the same setup previously tested (i.e., a quart container, a no. 8 detonator, and alight witness plate). The resultant acceleration measurements indicated that the transducers were bing subjected to peak accelerations in excess of 79,000 g's and the vibration loads exceed 26,000 g's peak to peak. It became obvious from these data that the transducers were being damaged by vibration loads and not side loads and that the transducers would have to be shock isolated. In order to shock isolate the transducers, it was decided to suspend the transducer within a metal fitting (that could be attached to the canister baseplate) and isolate the transducer from the fitting by potting it within the fitting using a suitable material.

Test No. 13. This test was a repeat of test 12 but with the new transducer support design. The test used a 1-qt container full of water, a no. 8 detonator, and the

light witness plate. The detonator was fired and the witness plare was launched to a height of 6.0 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The pressure transducer signal measured corresponded to a maximum peak initial pressure of 19,900 lb/in.^{2}, and the pressure trace indicated that the transducer had survived the event. The canister suffered minor damages consisting of bulging of the sidewalls through plastic deformation.

Test No. 14. This test was conducted on a 1/2-gal. container filled with water and using a no. 8 detonator cap. The new pressure transducer mounting design used in the previous test was again used. The initiator was fired and the 1/2-in. thick witness plare was launched approximately 12 feet. For this test, the witness plare velocity as measured from a video tape recording was 40 ft/s at the 2-ft height. Measured peak initial shock pressure was 25,600 ilb/in.^{2}. The canister suffered similar damage to previous tests consisting of bulging in the sidewalls.

Test No. 15. This test was conducted using the pint-size container full of water and the no. 8 detonator. The light witness plate was used, and the pressure transducer potted in the fitting was mounted in the canister baseplate. The detonator was initiated, and a peak initial pressure of 27,400 lb/in.^{2} was recorded. The witness plate was launched to a height of 5 feet. The witness plate velocity as measured from a video tape recroding was 14.3 ft/s at the 1-ft height. The entire pressure-time history was again recorded by the transducer and a post-test inspection of the canister showed minor damage consisting of sidewall bulging of the container.

Test No. 16. This test was a repeat of the previous test only with a higher input energy. A no. 8 detonator and 3/4 in. of the 80 grain per foot prima cord were inserted into the pint container. This yielded a combined total explosive weight of 12.78 grains. The container was filled with water and the light witness plate was positioned on top of the canister. The potted pressure transducer was mounted to the canister baseplate and the initiator was detonated. The light witness plate was launched to a height of 6.25 ft and an initial peak pressure in excess of 55,000 lb/in.^{2} was recorded. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. A review of the entire pressure record showed that once again, the transducer had been damaged and that erroneous date had been recorded coupled with a realistic pressure-time history.

Test No. 17. This test was performed using a quart container. The no. 8 detonator and the 3/4 in. of prima cord were used to produce a higher input energy. The container was filled with water and a new gage potted in the metal fitting as done in the previous successful tests was installed in the canister baseplate. The detonator was initiated and the witness plate was launched to a height of 6.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. A maximum initial shock peak pressure in excess of 15,500 lb/in.^{2} was

measured and once again, the transducer was severely damaged by the shock loads and erroneous high pressure data both positive and negative were recorded. As a result, the actual pressure-time history was not retrievable from the data. The canister suffered minor damage consisting of bulging in the sidewalls.

Test No. 18. This test was a repeat of the previous test and was performed because of suspicions that the transducer might have been damaged during initial installation. A new transducer was potted in the fitting and installed in the quart container. The container was filled with water and the no. 8 detonator and 3/4-in. prima cord were initiated. The resultant loads launched the light witness plare 8.0 ft into the air, and the container was slightly bulged. For this test, the witness plare velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. A review of the pressure data showed a maximum initial peak pressure of 20,200 lb/in.^{2} and also showed that the transducer survived the test.

Test No. 19. This test was conducted using the 1/2-gal. container full of water and the no.8 detonator and 3/4 in. of prima cord. The detonator was initiated, and the light witness plate was launched to a height of 17 feet. For this test, the witness plare velocity as measured from a video tape recording was 33.4 ft/s at the 1-ft height. The analysis of the pressure data indicated a maximum initial peak pressure in excess of 38,000 lb/in.^{2} and showed that once again, the transducer had been damaged by the shock loads and erratic high frequency, high pressure data were recorded over the actual time-pressure history rendering the data, other than the initial peak pressure, useless. It was decided that rather than continue testing at the higher energy levels with water and continue destroying transducers, that testing with the liquid propellant at the lower energies should be initiated. This would allow for comparisons to be made between the water filled and the liquid propellant filled containers at the lower energy level.

Test No. 20. This test was conducted using the 1/2 gal. canister filled with NOS 365 and using the light witness plate. A single no. 8 detonator was installed midway in the canister and initiated. The witness plate was launched to a height in excess of 28 ft and the maximum initial pressure measured was in excess of 32,500 lb/in.^{2}. For this test, the witness plate velocity as measured from a video tape recording was 50 ft/s at the 1-ft height. The analysis of the entire pressure data indicated that the transducer was severely damaged during the test and erroneous data was again recorded over the actual pressure-time history, preventing the extraction of the actual pressure-time history.

Accelerometer Tests. To measure the accelerations that the potted transducers were being subjected to, it was decided to pot an accelerometer in the same fitting as the transducer and perform tests to measure the accelerations. These tests indicated that the pressure transducers were still being subjected to large ac-

celerations that were damaging the transducers. In order to minimize the accelerations, it was decided that the pressure transudcer would have to be completely isolated from the canister and that the test setup should be more rigid and massive if the accelerations were to be damped. The pressure transducer was therefore mounted in a massive concrete pad so that the transducer protruded 1.5 in. above the concrete. A 1-in. steel baseplate with a large hole for the transducer was bolted to the concrete and the test canister was then bolted to the steel plate. The 1/2-in. canister baseplates also had a hole drilled for the transducer so that when the assembly was complete, the transducer fit flush with the inside bottom of the canister. The hole in the canister was drilled oversize to allow the baseplate to flex without loading the sides of the transducer, and the oversize was filled with a potting compound to insure a leak-proof seal.

Test No. 21. This test was performed using the new massive test fixture and a 1/2-gal. container filled with water, the light witness plate, and a single no. 8 detonator. The detonator was initiated and the witness plate was launched to a height of 16.5 feet. For this test, the witness plare velocity as measured from a video tape recording was 33.4 ft/s at the 1-ft height. A preliminary review of the peak initial pressure indicated a pressure of 10,000 lb/in.^{2}, and also indicated that the transducer had survived the test, and a record of the entire pressure-time history had been recorded. As was the case in the previous tests, damage to the canister was limited to bulging of the lower sidewalls, with no catastrophic failures.

Proof Tests

Test No. 22. This test was performed using 1/2 gal. canister filled with water. A single no. 8 detonator having an equivalent HMX explosive weight of 7.78 grains was employed. The test was conducted using a light witness plate (8 in. x 8 in. x 1/2 in.) which was launched to a height of 15.0 feet. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. The analysis of the pressure data showed that the pressure transducer measured an initial maximum peak pressure of 11,400 lb/in.^{2} and recorded the entire pressure-time history (fig. 3). The transducer appeared to survive the test undamaged, and the 1/2 gal. canister suffered minor damage which consisted primarily of some bulging in the sides of the canister. As before, no welds were broken, and the witness plate was not noticeably deformed.

Test No. 23. This test was a repeat of the previous test with the exception that this test used NOS 365 liquid propellant instead of water. The 1/2-gal. canister was filled with the liquid propellant; a no. 8 detonator was inserted midway into the canister; and then the 1/2-in. thick witness plate was placed on top of the canister. The detonator was initiated and the witness plate was launched to a height of 24 feet. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. The pressure recording was evaluated, and the transducer measured an initial peak of 17,500 psi. The initial peak pressure and the entire pressure-time history for

this test are shown in figure 4. The canister suffered major bulging in the sidewalls but no other major damage. The transducer survived the test and was reused on the next test.

Test No. 24. This test was performed using a quart container filled with water and was initiated by detonating a single no. 8 EBW detonator. The light (1/2-in. thick) witness plate used for this test. The detonator was initiated and the test launched the witness plate to a height of approximately 6.5 ft, and the canister suffered slight damage consisting of bulging in the sidewalls. For this test, the witness plate velocity as measured from a video tape recording was 40 ft/s at the 2-ft height. The analysis of the pressure trace (fig. 5) showed a maximum peak pressure of 14,250 lb/in.^{2}. The pressure-time history for this test and the fact that a second major pressure spike occurred shortly after the first spike are also shown in this figure. This second pressure spike could be the first reflection of the initial shock wave generated by the cap detonation.

Test No. 25. This test was a repeat of the previous test and used a quart filled with NOS 365 instead of water. A no. 8 detonator and the light witness plate lid were used for this test. The detonator was initiated and the witness plate flew 12.0 feet. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. The canister suffered minor damage consisting of slight bulging in the sidewalls. The analysis of the pressure data revealed a maximum initial peak pressure of 15,515 lb/in.^{2} (fig. 6) and also that a second pressure peak occurred shortly after the first. The second peak was more severe than the first peak and measured 12,710 lb/in.^{2}. The transducer measured the entire pressure-time history (fig. 6) and was reused in the next test.

Test No. 26. This test was performed using the pint canister filled with water. A no. 8 detonator was used, as was the light witness plate. The detonator was initiated and the witness plate was launched 5.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The pressure transducer data indicated a peak initial pressure of 21,000 lb/in.^{2} and several larger pressure peaks occurring later in the event (fig. 7). The maximum pressure measured was 52,857 lb/in.^{2}. As was the case in the previous tests, the canister suffered minor damages consisting of bulging in the sidewalls.

Test No. 27. This test was a repeat of test no. 26 but with the pint canister full of liquid propellant instead of water. A no. 8 detonator and the light witness plate were used for this test. The detonator was fired and the witness plare launched to a height of 9.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. The pressure transducer measured an

initial peak pressure of 13,800 lb/in.^{2} and recorded the maximum pressure of 24,800 lb/in.^{2} approximately 0.075 ms after the detonator was initiated. The entire pressure-time history is shown in figure 8. The canister suffered minor damage consisting of bulging in the sidewalls.

Test No 28. This test was conducted on a quart container filled with water andusing a no. 8 detonator cap and 3/4 in. portion of the prima cord. The larger detonator/prima cord configuration resulted in an energy of 3,817 ft-lb being applied to the canister. The initiator was fired and the 1/2-in. thick witness plate was launched approximately 9 feet. For this test, the witness plate velocity as measured from video tape recording was 33 ft/s at the 1-ft height. The pressure transducer output is shown in figure 9. Measured peak initial shock pressure was 16,800 lb/in.^{2} and once again, several large spikes were measured after the first. It appears that the later pressure spikes are the initial shock wave reflections as the wave travels in the canister. The canister suffered similar damage to previous tests consisting of bulging in the sidewalls.

Test No. 29. This test was conducted using the quart-size container full of NOS 365 liquid propellant instead of water and the no. 8 detonator with the 3/4-in. segment of prima cord. The light witness plate was again used and was launched to a height of 1.65 ft when the detonator was initiated. For this test, the witness plate velocity as measured from a video tape recording was 33 ft/s at the 1-ft height. The pressure transducer measured a peak initial pressure of 9,7000 lb/in.^{2} and a maximum pressure peak of 36,410 lb/in.^{2}. The maximum pressure recorded occurred later in the test as shown in figure 10. A post-test inspection of the canister showed minor damage consisting of sidewall bulging of the container.

Test No. 30. This test was performed using the 1/2-gal. container filled with water. A no. 8 detonator and 3/4 in. of the 80 grain per foot prima cord were detonated and the light witness plate was launched to a height of 23 feet. For this test, the witness plate velocity as measured from a video tape recording was 40 ft/s at the 1-ft height. The pressure transducer measured an initial peak pressure of 16,500 lb/in.^{2} and a maximum pressure of 48,400 lb/in.^{2} occurring approximately 0.060 ms after the initial peak pressure. The pressure-time history was recorded and is presented here as figure 11. A post-test inspection of the canister showed minor damage consisting of bulging in sidewalls.

Test No. 31. This test was a repeat of the previous test with the exception that it was performed using liquid propellant instead of water. The no. 8 detonator and the 3/4 in. of prima cord were used as was the light witness plate. The detonator was initiated and the witness plate was launched to a calculated height of 62 feet. For this test, the witness plate velocity as measured from a video tape recording was 66.7 ft/s at the 2-ft height. The pressure data recorded are shown in figure 12. A maximum initial

shock peak pressure of 10,700 lb/in.^{2} was measured and once again, several large pressure pulses occured later in the test. A review of the entire pressure-time history showed that late in the event, the pressure transducer appeared to have failed (approximately 0.150 ms after the detonator was initiated). By this time, the witness plate had already left the canister so the losses of the subsequent pressure data was not disastrous. The pressure-time history data necessary for the model is that which occurs before the plate is launched and that data was successfully recorded. The canister showed some major deformations in the sidewalls but no other adverse damages. Subsequent checks of the pressure transducer indicated that it was functioning normally. In order to check the transducer, it was decided to perform a repeat test using a quart canister.

Test No. 32. This test was conducted to verify the condition of the pressure transducer and was conducted on a quart canister using water, a light witness plate, and a no. 8 detonator and 3/4 in. of prima cord. The detonator was initiated and the light witness plate was launched to a height of 11.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 33.3 ft/s at the 1-ft height. A portion of the recording of the pressure-time history is presented in figure 13 and a maximum initial peak pressure of 15,800 lb/in.^{2} was recorded. The maximum pressure measured was 38,900 lb/in.^{2} and occurred approximately 0.060 ms after the first peak. A review of the later pressure recording showed that once again the transducer appeared to have been damaged. The pressure transducer was removed from the concrete and was found to have a break in the cable. The cable was repaired and the transducer was checked out and reinstalled in the concrete pad.

Test No. 33. This test was performed using the quart canister filled with water and using the larger RP 83 detonator. This detonator imparted a higher energy of 4,917 ft-lb into the canister. The detonator was initiated and the resultant loads launched the light witness plate to a height of 8 ft into the air. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. A review of the pressure data showed a maximum initial peak pressure of 15,800 lb/in.^{2} and also showed a second larger pressure pulse occurring later in the test (fig . 14). Thios larger pressure was approximately 28,000 lb/in.^{2} and occurred approximately 0.050 ms after the initial peak. The post-test inspection revealed minor damages to the canister.

Test No. 34. This test was conducted using the quart canister filled with NOS 365 and using the light witness plate. The larger RP 83 detonator was installed midway in the canister and initiated. The witness plate was launched to a calculated height of 86.9 ft and the maximum initial pressure measured was 17,310 lb/in.^{2} (fig. 15). For this test, the witness plate velocity as measured from a video tape recording was 75 ft/s at the 2-ft height. The analysis of the entire pressure data indicated that the initial peak was the largest pressure recorded and post-test inspection showed that the

canister was violently ripped in the test (figs. 16 and 17). The witness plate was severely deformed in the test and a review of the video recording showed that some of the liquid propellant became involved and deflagrated resulting in the destruction of the canister. Three-quarter canisters and 3 pint canisters have been tested and the relative damage that these canisters have suffered is shown in figure 18. None of the canisters have been damaged as severely as the quart canister.

Test No. 35. This test used a 1/2-gal. container filled with water and an RP-83 detonator. The test was conducted using a light witness plate. The detonator was initiated and the witness plate was launched to a calculated height of 24 feet. For this test, the witness plate velocity as measured from a video tape recording was 50 ft/s at the 1-ft height. The initial peak pressure as measured by the pressure transducer was 20,300 lb/in.^{2}. The transducer recorded the entire pressure-time history without any apparent damage, and the canister itself suffered only deformations in the sidewalls.

Test No. 36. This test was a repeat of the previous test using a 1/2-gal container only. The canister was filled with NOS 365 liquid propellant instead of the water. An RP-83 detonator was used to deliver the 4,917 ft-lb of energy and the initiation of the detonator resulted in the light witness plate being launched to a calculated height of 38 feet. For this test, the witness plate velocity as measured from a video tape recording was 50 ft/s at the 1-ft height. The initial peak pressure was measured at 21,380 lb/in.^{2}. The canister suffered minor damages to the sidewalls consisting of minor bulging. The pressure transducer recorded the pressure-time history (fig. 20).

Test No. 37. This test was performed using the pint canister filled with water, with the light witness plate and the RP-83 detonator. The detonator was initiated and the witness plate was launched to a height of 6 feet. For this test, the witness plate velocity as measured from a video tape recording was 20 ft/s at the 1-ft height. The initial peak pressure as measured by the pressure transducer was 21,600 lb/in.^{2} and the pressure-time history is presented in figure 21. The transducer appeared to have survived the tests undamaged and the canister suffered only minor bulging in the lower sidewalls.

Test No. 38. This test was a repeat of the previous test using NOS 365 instead of water. The pint canister was filled with the liquid propellant and an RP-83 detonator was placed midway up the canister. The detonator was functioned and the liquid propellant became involved and either deflagrated or burned very rapidly, generating such large pressures that the canister was totally destroyed and only the canister baseplate remained attached to the steel mounting base (fig. 22). The canister fragmented into numerous large fragments of which only a small number were recovered (figs. 23 and 24). The witness plate was launched well out of camera range; however, the video camera was able to capture the witness plate as it fell to the ground thereby

providing a measure of the total time that the plate was in the air. From this total air time, it was possible to estimate the height that the plate traveled as being over 468 feet. The witness plate velocity was calculated as 174 ft/s. A post-test examination showed that the witness plate was severely deformed and the pressure transducer was also damaged in the test. The initial peak pressure and the pressure-time histroy are presented in figure 25 and the peak initial pressure was measured as being 21,400 lb/in.^{2}. It was decided that since only two tests remained, and these tests involved the pint canister filled with water and with LP, and rather than dismantle the setup to install a new pressure transducer, the tests with pints would be conducted to measure. Only here, the witness plate heights and pressures would not be recorded.

Test No. 39. This test used a pint container filled with water and was conducted at the mid-energy range using a no. 8 detonator and 3/4 in. of prima cord. The pressures were not recorded and this test was performed to measure the witness plate height only. The detonator was initiated and the witness plate was launched to a height of 7 feet. For this test, the witness plate velocity as measured from a video tape recording was 25 ft/s at the 1-ft height. The canister suffered minor damages consisting of bulging in the sides.

Test No. 40. This test was performed with a pint container and a no. 8 detonator with 3/4 in. of prima cord and using NOS 365 liquid propellant instead of water. As was the case in the previous test, pressures were not recorded on this test. The detonator was initiated and the witness plate was launched to a height of 17.5 feet. For this test, the witness plate velocity as measured from a video tape recording was 22 ft/s at the 1-ft height. A post-test inspection revealed similar minor damages to the container.

DATA ANALYSIS

During the experiments, particularly during the preliminary test, data interpretation difficulties were encountered as a result of erroneous pressure signals. The bad data were produced by the severe shock and vibration loads on the pressure transducer, a PCB Piezotronics, Inc. Model 109A02. This 120,000 lb/in.^{2} rated sensor is qualified to withstand mechanical shock loads of 20.000 g's and vibration of 2,000 g's. Before finding appropriate shock isolation mounting, the transducer would occasionally give good signals and survive. Initially good signals were received, but then suffered internal circuitry damage. This damaged occurred at a very early time near initial, peak blast pressure shock-up. To eliminate suspicions about transducer integrity, and see if measurements were of the right order of magnitude, the following equation was extracted from Cole's Underwater Explosions which gives pressure as a function of the reciprocal of the explosive weight scaled distance from the charge

$$P_m = k(w^{1/3}/R)^a$$

where pressure is in lb/in.^{2}, weight is in pounds TNT equivalent, distance is in feet, k is 21,600 and a is 1.13. For experiments using water, table 3 was constructed to show that proof test phase experimental pressure measurements were of the right magnitude.

To provide insight into developing a data correlation mathematical model based on observed and recorded phenomena, some preparatory analysis was performed on the primitive variable data taken and predicted. Plots of energy versus witness plate heights have been generated for those tests performed on the rigid concrete baseplate (tests 22 to 40). The witness plate height versus energy for all of the tests is shown in figure 26. Present comparisons of the water tests versus the liquid propellant tests for the 1/2-gal. containers, the quart containers, and the pint containers are shown in figures 27 through 29, respectively. The witness plate height data have also been plotted as a function of energy per unit volume (fig. 30).

MODEL AND DATA CORRELATION

Introduction

The model developed for this study is a phenomenological, physical model based on the experimental data taken. It was decided at the outset of this project work to chose what measurements to make and then base a model on measured parameters. The data measurements were the same type as those made in other, earlier studies related to liquid gun propellant vulnerability and, in that sense, the measurements made during this study give this work continuity to previous work. However, the model correlates the data of this work only and does not incorporate data from the other work.* It is intended to correlate the less-than-full scale experiments of both types, high-explosive and shaped-charge shots into LP filled canisters, at a future time following more in-depth evaluations and field tests. Large-scale to full-scale test results can then be used to calibrate model correlations. One outcome will be design methodology for vulnerability reduction.

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* An example of previous work is reported by W.O. Seals in the 1983 JANNAF Propulsion Systems Hazards Subcommittee Meeting, Vol. 1, July 1983, and in Seals' report BRL-TR-2646 (April 1985) where shaped charges were shot into canisters filled with NOS 365.

The modeling relates the input energy to the observed output impulse and momentum. The purpose of the model is to provide an analytic means with which the hydraulic ram effect caused by shooting a shaped charge through a liquid propellant-filled container may be estimated, for a reduced scale, by correlating data from experiments which simulate shaped charge effects by release of explosive energy from a high-explosive detonation. It is intended that use and application of the model will provide the means to better understand the hydraulic ram effect caused by full-scale shaped charge impacts into liquid propellant containers and to design full-scale liquid propellant containers for reduced vulnerability. For thoroughness and completion and to use the model as a design aid in the future, however, it will be necessary to calibrate and adjust the model. Supplementary experimental data that incorporate larger-scale test results as well as shaped charge experimental test results from reduced scale experiments will be considered.

The model to be described is based on correlating the computed impulse per unit area (i.e., specific impulse) given by the time integral of the pressure that was measured on the base of the canisters to the momentum of the witness plate. As is the custom, impulse is treated as a parameter that handily scales to represent explosive output phenomena. Witness plate momentum was reduced to water equivalent by scaling with the fluid impedance and is considered in terms of the relative surface area of the canister in contact with the plate. The relative wetted area of the internal surface area of the canister was also considered. However, internal surface area consideration did not improve the correlation of the experimental data.

The correlation results are functionally dependent on the energy produced by detonation of the explosive in the canister. This parametric functionality is considered in the absolute sense and in terms of the specific energy per unit volume.

The background for the energy density of explosive relative to the potential for a shaped charge to impart part of its kinetic energy into the fluid is described and used to lend credence to the quantity of explosive employed in these experiments. These scaling considerations are provided in the following section.

Scaling

The performance of two typical shaped charges, the 81 mm (approx 3 in.) and the 127 mm (5 in.), are relatively well-known (see ARBRL-TR-02159 by Majerus and Scott, April 1979) and data for these shaped charges were used to determine the range of the quantities of high explosive that were used in these sub-scale experiments. The jet tip velocities of the 81-mm shaped charge is approximately 7.60 km/s according to Majerus and Scott. The jet tip velocity for the 127 mm is approximately 8.10 km/s and, like the 81 mm, the material is copper. The diameter of the lead jet particles for the 81-mm shaped charge is about 5.0 mm and for the 127-mm shaped charge the diameter of the lead particles is 8.0 mm.

Assuming that the energy transfer from a shaped charge jet to a fluid (liquid propellant) in a container occurs by deposition of a portion of the shaped charge jet kinetic energy, a complementary concept has been proposed. There is a corresponding energy input that can be obtained from other very rapid energy addition sources to better quantify shaped charge effects with less than full-scale experiments. These are conducted with less difficulty and at lower cost. Particularly, the transfer of the energy may be by means of an explosion blast from an equivalent-energy high explosive blast that produces a similar effect on the fluid with regard to hydraulic ram. In addition, the concept is that the effect of the blast can be related, through correlation of data, to attack on a canister of fluid by a shaped charge and then used to assess liquid propellant and container vulnerability to shaped charges.

Comments and reporting by W.O. Seals (e.g., 1983 JANNAF Propulsion Systems Hazards Subcommittee Meeting, Vol. 1, July 1983) reveal that shaped charge jets are expected to pass through canisters when a shaped charge is shot directly into the liquid containing space of the canister. In part, this is due to the relatively small size of the canisters of interest. Therefore, it is reasonable to assume that the portion of the shaped charge jet kinetic energy "consumed" by the liquid is not great for typical liquid propellant drum canisters of sizes that may contain as much as 20 to 30 gallons. A large part of the jet passes through canister sizes of interest. However, if it is assumed that the jet kinetic energy going into the impact event on the liquid is equivalent to the kinetic energy from a ten lead particle diameter lengths portion of the jet's mass, then the corresponding jet mass is 8.7 grams for the 81-mm shaped charge and 35.8 grams for the 127-mm shaped charge. These assumptions result in energy transfer to the fluid of approximately 185,200 ft-lbf (251,200 J) and 866,000 ft-lbf (1,174,400 J) for the 81-mm and 127-mm shaped charges, respectively.

On a volume basis, 20- to 30-gal, drums of liquid propellant are 80 to 120 times the intermediate size quart container used for the experiments conducted in these test series. On an energy per unit volume of liquid basis, where the full-scale to sub-scale volume is approximately a factor, the sub-scale energy per unit quart volume would be between 1,852 and 8,660 ft-lbf. The RP83 detonator was selected as an appropriate quantity of high explosive because it has approximately 5,270 ft-lbf of energy. This scaled value of energy is representative of a full scale shaped charge fired through stored propellant in full scale drums.

Data Correlation

Test data was used to construct table 4 to present the model that was developed. These data include the specific energy which was obtained by determining the energy input on the basis of the quantity of liquid present. This provides energy per unit volume of liquid and represents how the explosive energy input is distributed over the liquid mass. Specific impulse was obtained by integrating the pressure signals that were recorded. It is a characteristic quantity that is a standard parameter used in

determining damage or damage potential and structural loading due to blast or other transient forces. The witness plate height given was taken normally from a video tape playback analysis. If the witness plate was off the view screen, then the time that the witness plate was in upward flight and fall was used to compute the height. To provide a direct comparisons between the specific impulse and momentum of the witness plate, the witness plate height data were scaled by the contact area between the plate and the liquid. The contact area is the canister cross-sectional area in the case. Also, to provide correlation between specific energy and momentum, the momentum result for water was multiplied by the square root of the impedance parameter ratio for liquid propellant over that of water. This ratio as well as several other data and comments are provided as notes on table 4.

Analysis

The data model analysis correlations are presented in two figures (figs. 31 and 32). The witness plate specific momentum versus the specific energy is presented in figure 31. Good correlation of data is provided except for those tests where reaction took place. On the basis of the agreement between the two modeling parameters, it appears feasible to use sub-scale experiments like those conducted to provide information on large- or full-scale configurations of propellant containing canisters.

The comparison of specific momentum and specific impulse is shown in figure 32. Ideally, the data should fall on a line. It appears that pressure measurements were slightly low or more of the wave form should be considered and integrated to obtain specific impulse. It is reasoned that witness plate momentum seems to exceed the impulse in nearly all cases partly on physical ground and partly on pressure measurement and signal recording grounds. It appears also that the witness plate continues to be propelled by the liquid flowing ahead of the bubble pulse in the canister after the pressure transducer signal drops to a pressure much lower than initial blast and shock pressures. Additional explanation is given in table 4 and in the conclusions of this report.

CONCLUSICNS AND RECOMMENDATIONS

1. Some test results show that the possibility exists for liquid propellant to undergo chemical reaction (rapid decomposition or probably combustion) due to the energy imparted from a shaped charge impact. Such reactive behavior can be very important to the vulnerability of the system and crew handling and transporting liquid propellant in a combat environment. It is imperative to evaluate and understand the scenario, conditions, and circumstances surrounding liquid propellant in containers under such challenge and recommend other experiments be performed to evaluate the phenomena and develop mitigation techniques for full and partially full containers

2. The test program demonstrated the difficulties encountered with making pressure measurements in test involving simulated shaped charge impacts. The resultant shock and vibration loadings to the test fixture were much more severe than anticipated, thereby complicating and limiting the use of the conventional pressure transducers in these applications. It is recommended that alternate pressure measurement techniques be evaluated for possible use in these types of testing circumstances.

3. Since this project evaluated hydraulic ram effects using cylindrical containers, it is recommended that additional tests and analysis be performed using other container shapes and larger container sizes. The current test program employed fairly small quantities of NOS 365 liquid propellant (i.e., pint, quart, and 1/2-gal. quantities). Experiments should be performed using larger amounts to determine the influence of container shape and size on the sensitivity of liquid propellant to high-explosive detonation and shaped charge penetration stimuli. Also, the level of liquid fill, container internal structure, ullage effects, and shaped charge entry direction need to be addressed.

4. It appears that there is an energy input level or plateau above which a chemical reaction in a container of liquid propellant is contributory to hydraulic ram related damage potential. It is recommended that additional tests and analysis be performed using greater range of input energy and characteristic size. The charge weight should be increased for these tests. Also, the container size (e.g., height and diameter) and subsequent charge standoff distance from a container wall or upper and lower ends should be varied as well as the degree of confinement that is provided. Canister materials and thickness may also be varied to obtain different confinement as may an ullage above the liquid.

5. From analysis and modeling of the data, it appears that either pressure measurements were slightly low or more of the wave form needs to be considered and integrated to obtain the specific impulse. Reasoning is that witness plate momentum appears to exceed the impulse in nearly all cases. However, the witness plate may continue to be boosted by the jetting-up liquid after the pressure transducer discontinues to sense pressure due to the outflow of liquid.

6. Specific energy and specific witness plate momentum correlate well. Correction of conversion of witness plate height results for water was made to put the water results on the same basis as liquid propellant results. This correction was accomplished by using the liquid impedance ratio parameter. This comparable basis correction to the height data for water appears to be successful. It is recommended, however, that the modeling effort be continued further with some effort given to developing strictly computationally based methods to describe hydraulic ram effects.

7. For two of the experiments conducted with liquid propellant there definitely was a reaction mechanism of some origin. It appears to be a very rapid deflagration or detonation during one of the tests. These reactions appeared to occur after the witness

plate lifted-off from the container which explains why the pressure and impulse determined from the pressure do not definitively reveal the reaction mechanism. It appears that the mist or vapor reacted and the witness plate was boosted to a considerable height, not characteristic of hydraulic ram alone. It is recommended that a sample of the NOS 365 used for this work be evaluated by chemical analysis and that the concept of a critical input energy plateau be investigated with both NOS 365 and other liquid propellant formulations.

Table 1. Liquid propellant tests

Test no.	Container size	Liquid type	Energy input (ft-lb)	Prima cord length (in.)	Witness plate weight (lb)	Plate height (ft)	Initial peak pressure (lb/in.^{2})
1[1]	1/2 gal	Water	4,917	None	9.2	20.5	34,840[a]
2[1]	1/2 gal	Water	9,834	2.4	9.2	64	30,488[a]
3[1]	1/2 gal	NOS 365	4,917	None	9.2	27	24,000[a]
4	1/2 gal	Water	2,306	None	18.3	9.5	25,854[b]
5[3]	1/2 gal	Water	2,306	None	18.3	5.75	30,000
6[3]	Quart	Water	2,306	None	18.3	2.6	8,010
7[3]	1/2 gal	Water	2,306	None	18.3	7	7,100
8[4]	1/2 gal	Water	2,306	None	18.3	6.5	19,840 5,780
9[4]	1/2 gal	Water	2,306	None	18.3	6.0	24,263 4,875
10[5]	Quart	Water	2,306	None	9.2	6.3	24,370
11[5]	Quart	Water	2,306	None	9.2	7.0	21,000[b]
12[6]	Quart	Water	2,306	None	9.2	5.5	26,000[b]
13[7]	Quart	Water	2,306	None	9.2	6.0	19,908
14[7]	1/2 gal	Water	2,306	None	9.2	12.0	25,595
15[7]	Pint	Water	2,306	None	9.2	5.0	27,373
16[7]	Pint	Water	3,817	3/4	9.2	6.25	54,900[b]

Table 1. (cont)

17[7]	Quart	Water	3,817	3/4	9.2	6.5	15,500[b]
18[7]	Quart	Water	3,817	3/4	9.2	8.0	20,202
19[7]	1/2 gal	Water	3,817	3/4	9.2	17.0	38,055[a]
20[7]	1/2 gal	NOS 365	3,817	3/4	9.2	28.0	32,500[a]
21[8]	1/2 gal	Water	2,306	None	9.2	16.5	10,010
22[8]	1/2 gal	Water	2,306	None	9.2	15	11,421
23[8]	1/2 gal	NOS 365	2,306	None	9.2	24	17,500
24[8]	Quart	Water	2,306	None	9.2	6.5	14,252
25[8]	Quart	NOS 365	2,306	None	9.2	12	12,714
26[8]	Pint	Water	2,306	None	9.2	5.5	21,026
27[8]	Pint	NOS 365	2,306	None	9.2	9.5	13,795
28[8]	Quart	Water	3,817	3/4	9.2	9.0	16,667
29[8]	Quart	NOS 365	3,817	3/4	9.2	16.5	9,700
30[8]	1/2 gal	Water	3,817	3/4	9.2	23	16,538
31[8]	1/2 gal	NOS 365	3,817	3/4	9.2	62	10,726
32[8]	Quart	Water	3,817	3/4	9.2	11.5	15,855
33[8]	Quart	Water	4,917	None	9.2	8.0	15,833
34[8]	Quart	NOS 365	4,917	None	9.2	86.9	17,316
35[8]	1/2 gal	Water	4,917	None	9.2	24.0	20,359

Table 1. (cont)

36[8]	1/2 gal	NOS 365	4,917	None	9.2	38.0	21,385
37[8]	Pint	Water	4,917	None	9.2	6.0	21,590
38[8]	Pint	NOS 365	4,917	None	9.2	468	21,385
39[8]	Pint	Water	3,817	3/4	9.2	7.0	N/A
40[8]	Pint	NOS 365	3,817	3/4	9.2	17.5	N/A

NOTES:

1 - Pressure transducer mounted directly into baseplate.
2 - Pressure transducer mounted in a nylon insert.
3 - Pressure transducer mounted on an offset tube arrangement.
4 - Two pressure transducers used, one in a nylon insert, another on the offset tube arrangment.
5 - Pressure transducer mounted in a metal fitting, isolated from the canister baseplate by a nylon bushing.
6 - Pressure transducer mounted in 1-in. steel mounting plate, canister placed over transducer and potted with RTV.
7 - Pressure transducer potted in a fitting.
8 - Pressure transducer potted in concrete slab, 1-in. steel plate bolted to the concrete pad [illegible] canister baseplate bolted to the steel plate.

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[a] Pressure transducer damaged during this test, and the initial peak reflected overpressure occurs about the time of damage onset and may be erroneous.

[b] Pressure transducer damaged during this test, but initial peak reflected overpressure occurs prior to the damage onset and may not be erroneous.

Table 2. Liquid propellant tests - witness plate velocities

Test no.	Container size	Liquid type	Witness plate weight (lb)	Velocity, ft/s 1 ft	2 ft	4 ft	5 ft	Maximum height (ft)
1[1]	1/2 gal	Water	9.2	40	33	33	33	20.5
2[1]	1/2 gal	Water	9.2	--	66.7	60	56.3	64
3[1]	1/2 gal	NOS 365	9.2	--	42.9	40	--	27
4[2]	1/2 gal	NOS 365	18.3	20	22.2	22	21	9.5
5[3]	1/2 gal	Water	18.3	20	20	18	14	5.75
6[3]	Quart	Water	18.3	12.5	11.1	8	--	2.6
7[3]	1/2 gal	Water	18.3	20	20	20	17.6	7
8[4]	1/2 gal	Water	18.3	20	20	16.7	15.6	6.5
			Brk wire	16	13.6			
9[4]	1/2 gal	Water	18.3	20	18	16	15.2	6.0
10[5]	Quart	Water	9.2	16.7	16.6	16	15	6.3
			Brk wire	17.2				
11[5]	Quart	Water	9.2	20	20	18.2	16.7	7.0
			Brk wire	20				
12[6]	Quart	Water	9.2	20	20	16	13.9	5.5
13[7]	Quart	Water	9.2	20	20	17.4	14.3	6.0
14[7]	1/2 gal	Water	9.2	--	40	25	25	12.0
15[7]	Pint	Water	9.2	14.3	13	11.4	--	5.0
16[7]	Pint	Water	9.2	20	20	16	14.3	6.25

Table 2. (cont)

17[7]	Quart	Water	9.2	20	20	17.4	16		6.5
18[7]	Quart	Water	9.2	25	22.2	21	20		8.0
19[7]	1/2 gal	Water	9.2	33.4	33.4	33.4	33.4		17.0
20[7]	1/2 gal	NOS 365	9.2	50	50	40	41.7		28.0
21[7]	1/2 gal	Water	9.2	33.4	37.5	33	33		16.5
22[8]	1/2 gal	Water	9.2	25	28.6	28.6	29		15.0
23[8]	1/2 gal	NOS 365	9.2	25	33	33	36		24.0
24[8]	Quart	Water	9.2	--	40	25	21.8		6.5
25[8]	Quart	NOS 365	9.2	25	25	25	25		12.0
26[8]	Pint	Water	9.2	20	20	20	17.8		5.5
27[8]	Pint	NOS 365	9.2	25	23.1	23.5	21.7		9.5
28[8]	Quart	Water	9.2	33	25	22.2	20		9.0
29[8]	Quart	NOS 365	9.2	33	28.6	30.7	29.4		16.5
30[8]	1/2 gal	Water	9.2	40	42.9	40	38.5		23.0
31[8]	1/2 gal	NOS 365	9.2	--	66.7	57	55.6		62.0
32[8]	Quart	Water	9.2	33.3	28.6	26.7	25.0		11.5
33[8]	Quart	Water	9.2	25	22	21	20.8		8.0
34[8]	Quart	NOS 365	9.2	--	75	80	83		86.9
35[8]	1/2 gal	Water	9.2	50	40	40	38.5		24.0

Table 2. (cont)

36[8]	1/2 gal	NOS 365	9.2	50	42.8	44.4	50		38.0
37[8]	Pint	Water	9.2	20	20	18.75	--		6.0
38[8]	Pint	NOS 365	9.2	Canister Fragmented			Est. Ht.		486.0
39[8]	Pint	Water	9.2	25	22	20	17.8		7.0
40[8]	Pint	NOS 365	9.2	33	33	33	33		17.5

NOTES:

1 - Pressure transducer mounted directly into baseplate.
2 - Pressure transducer mounted in a nylon insert.
3 - Pressure transducer mounted on an offset tube arrangement.
4 - Two pressure transducers used, one in a nylon insert, another on the offset tube arrangement.
5 - Pressure transducer mounted in a metall fitting, isolated from the canister baseplate by a nylon bushing.
6 - Pressure transducer mounted in 1-in. steel mounting plate, canister placed over transducer and potted with RTV.
7 - Pressure transducer potted in a fitting.
8 - Pressure transducer potted in concrete slab, 1-in. steel plate bolted to the concrete pad with canister baseplate bolted to the steel plate.

Table 3. Peak blast pressure predictions for hydraulic RAM/liquid propellant tests using water filled containers comparisons to measured peak pressures

Test no.	Container L/2 (ft)	Explosive weight ^1/3 (lb ^1/3)	W^1/3 R	Predicted peak pressure (lb/in.^{2})	Measured peak pressure (lb/in.^{2})
22	0.177	0.1169	0.660	13,500	11,421
24	0.204	0.1169	0.570	11,440	14,252
26	0.135	0.1169	0.866	18,360	21,026
28	0.204	0.1392	0.680	13,970	16,667
30	0.177	0.1392	0.786	16,450	16,538
32	0.204	0.1392	0.680	13,970	15,855
39	0.135	0.1392	1.030	22,330	N/A
33	0.204	0.1508	0.739	15,350	15,833
35	0.177	0.1508	0.850	17,980	20,359
37	0.135	0.1508	1.120	24,550	21,590

NOTE:

1. Weights of explosive are 11.3 grains, 18.7 graims, and 24.0 grains TNT equivalent (0.0016 lb, 0.0027 lb, and 0.00343 lb) W^1/3 = 0.1169, 0.1392. and 0.1508 lb. ^1/3.

2. R = Distance to x-ducer from charge: pt--0.135 ft, qt.--0.204 ft, and 1/2 gal.--0.177 ft.

Table 4. Hydraulic RAM/liquid propellant data correlation

Test no.	Container size	Liquid type	Energy input (ft-lb)	Specific energy (ft-lb/in^3)	Specific impulse (lb/in.^{2}-ms)	Witness plate height (ft)	Plate specific momentum (lb/in.^{2}-ms
22	1/2 gal.	Water	2,306	20.1	295 (295)	15.0	442
23	1/2 gal.	NOS 365	2,306	20.1	380 (380)	24.0	413
24	Quart	Water	2,306	40.0	370 (300)	6.5	669
25	Quart	NOS 365	2,306	40.0	360 (250)	12.0	671
26	Pint	Water	2,306	79.5	950 (645)	5.5	809
27	Pint	NOS 365	2,306	79.5	400 (260)	9.5	788
30	1/2 gal.	Water	3,817	33.2	625 (225)	23.0	547
31	1/2 gal.	NOS 365	3,817	33.2	600 (140)	62.0	663
28	Quart	Water	3,817	66.3	475 (330)	9.0	788
32	Quart	Water	3,817	66.3	920 (320)	11.5	889
29	Quart	NOS 365	3,817	66.3	625 (225)	16.5	788
39	Pint	Water	3,817	131.7	--	7.0	919
40	Pint	NOS 365	3,817	131.7	--	17.5	1,070
35	1/2 gal.	Water	4,917	42.8	410 (410)	24.0	559
36	1/2 gal.	NOS 365	4,917	42.8	410 (410)	38.0	520
33	Quart	Water	4,917	85.4	345 (345)	8.0	741
34	Quart	NOS 365	4,917	85.4	250 (250)	86.9	1,808
37	Pint	Water	4,917	169.6	390 (390)	6.0	848
38	Pint	NOS 365	4,917	169.6	415 (415)	468.0	5,533

NOTES:

A. NOS 365 density is, nominally, 1.4022 g/ml and the (acoustic) velocity of sound at 20°C id, nominally, 1,930 m/s (6,335 ft/s). Water has sound velocity of 1,480 m/s (4,860 ft/s). Therefore, the impedance ratio of the two liquids is 1.83.

B. The following geometrical characteristics of the containers have been used in the above table of results:

1. 1/2 gal.: volume = 115.01 in.^{3}, area = 27.06 in.^{2}, internal surface area = 132.49 in.^{2}
2. quart: volume = 57.62 in.^{3}, area = 11.76 in.^{2}, internal surface area = 83.09 in.^{2}
3. pint: volume = 28.99 in.^{3}, area = 8.92 in.^{2}, internal surface area = 52.25 in.^{2}

C. On the tests listed above, the witness plate weight = 9.15 lb. Some preliminary tests employed a plate weighing 18.11 lb.

D. Specific impulse within ( )'s are values obtained after definite plateaus in integrated prssure signals are reached, usually following the first set of pressure wave signals obtained. Subsequent wave sets either increase the impulse in a stepwise fashion or, more or less, in a continuously increasing manner. Any apparent reduction in impulse is an unreal artifact associated with the recorder. There is no reason to use only the first plateau of impulse when more than one plateau occurs--the values within the ( )'s are provided to show the impulse associated with the first distinct set of shock waves. Except for test no. 38, approximately 0.15 ms of recorded data was used to determine the impulse. On test 38 the pressure transducer was damaged after the first wave set.

E. Witness plate momentum is computed from plate height and not from measured witness plate velocities. The momentum per unit area is referred to as specific momentum based on the contact area of the plate and the liquid. The specific energy is based on the volume of liquid. Witness plate heights for water were converted to NOS 365 by multiplying by the fluids' impedan^e ratio when used to determine the momentum.

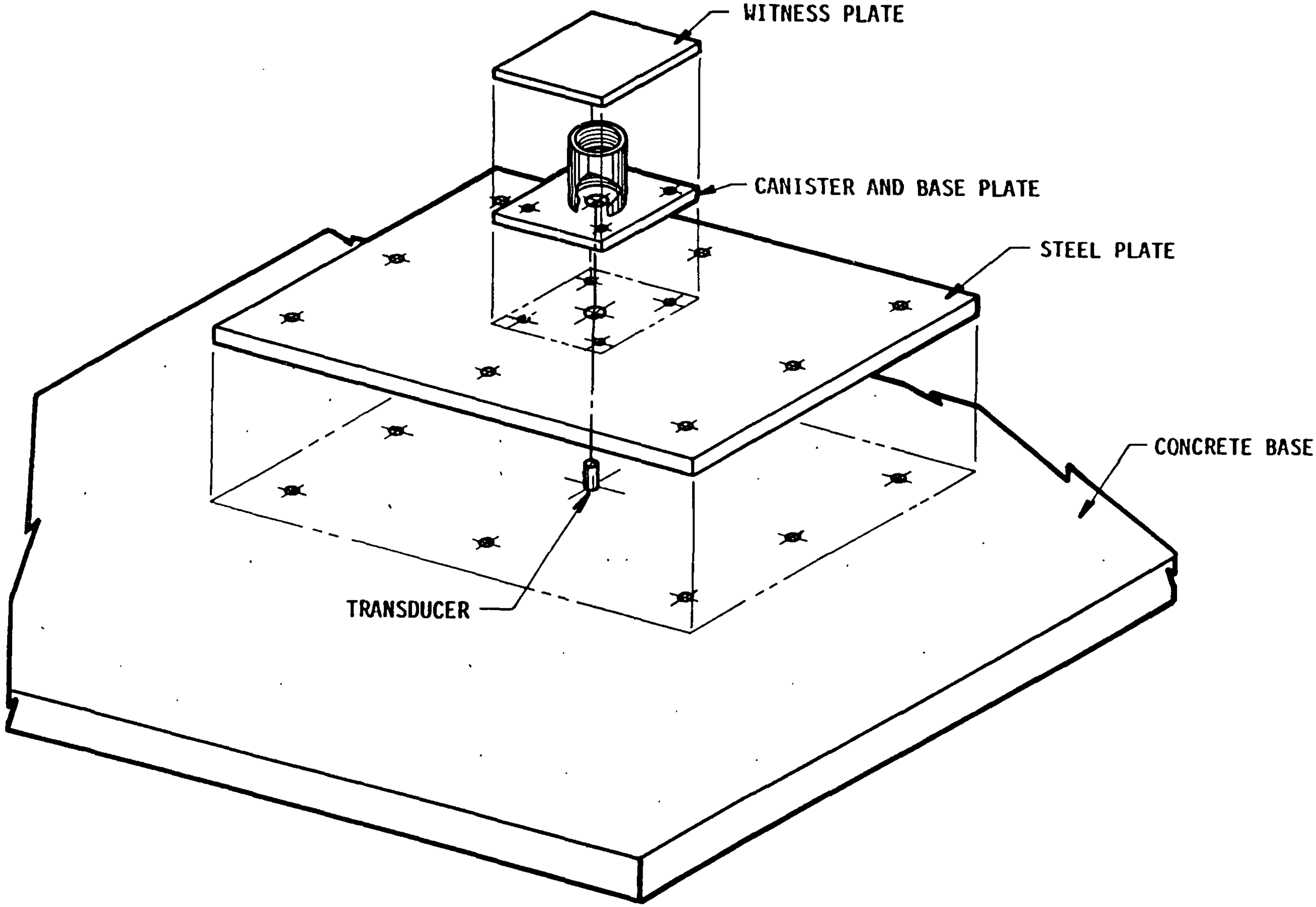
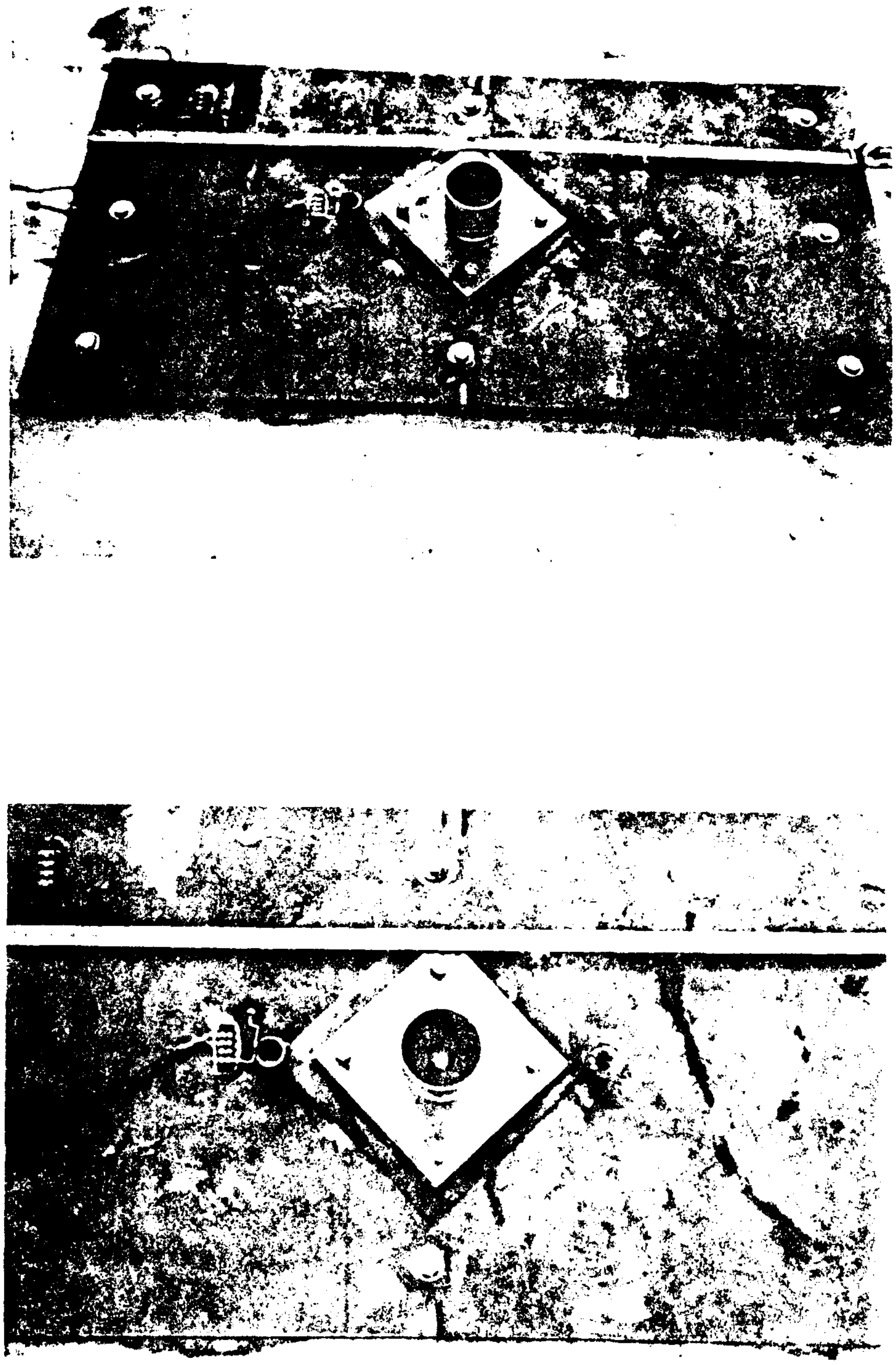
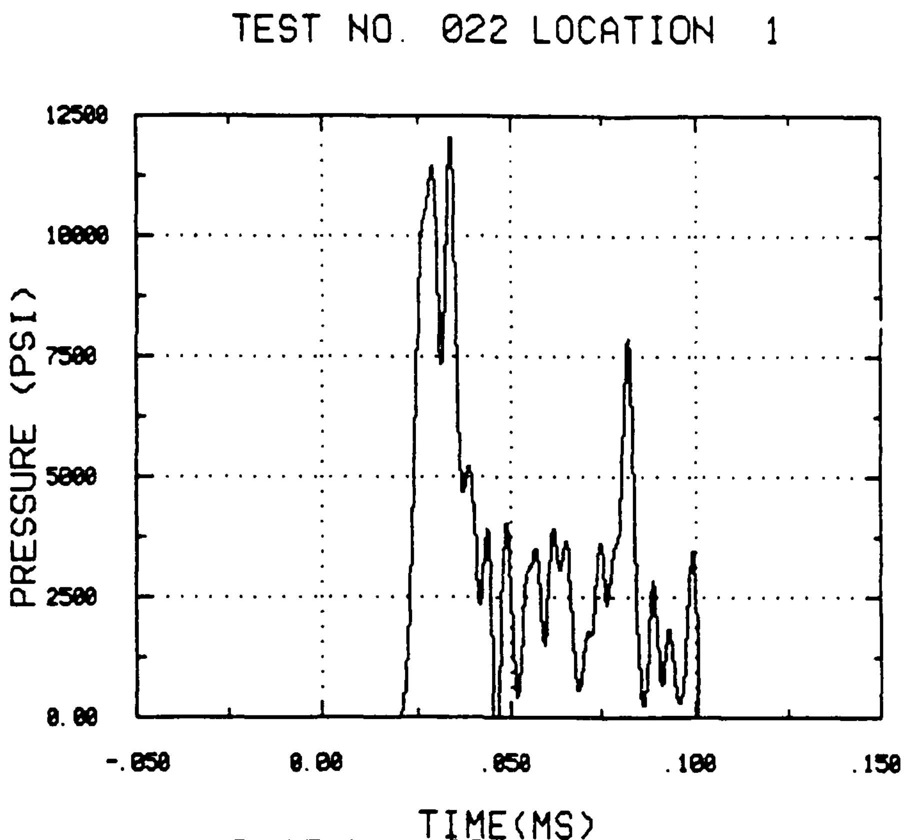


Figure 1. Test setup



NOTE: View inside pint container, presurre transducer in center

Figure 2. Pint container mounted on test configuration



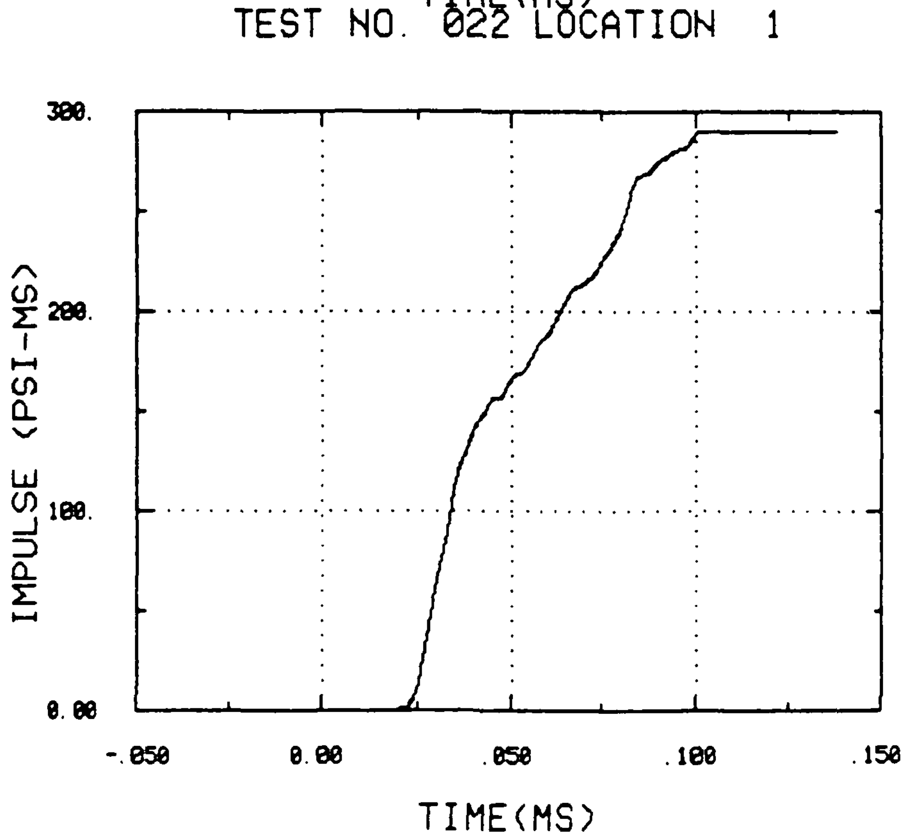
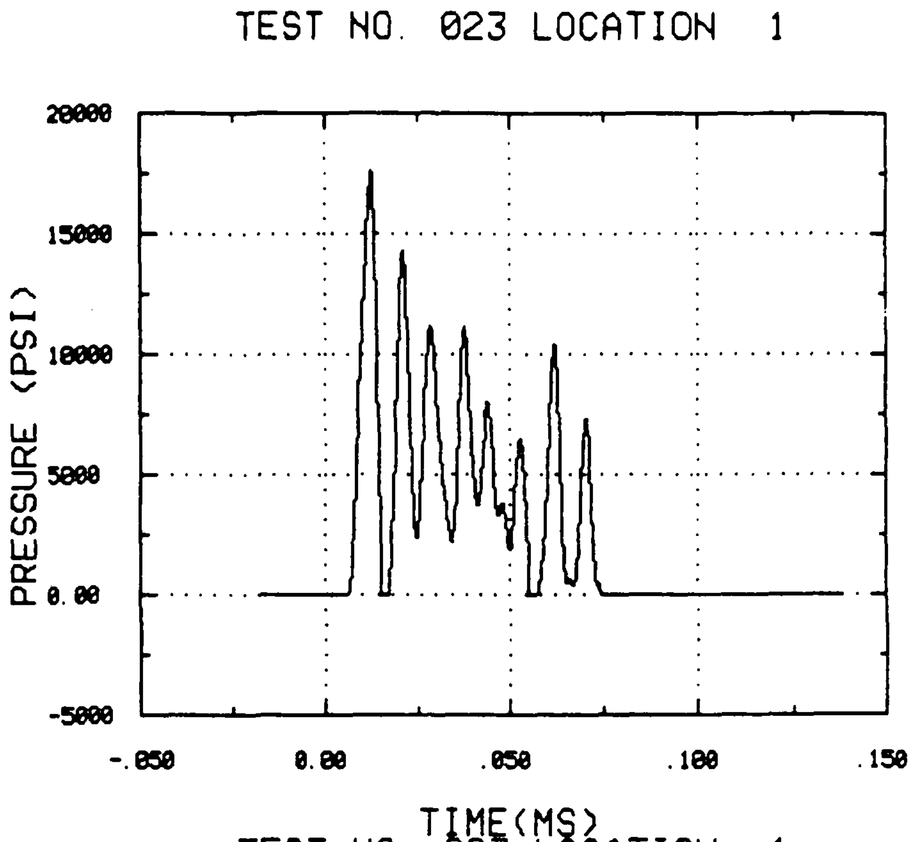


Figure 3. Test no. 22



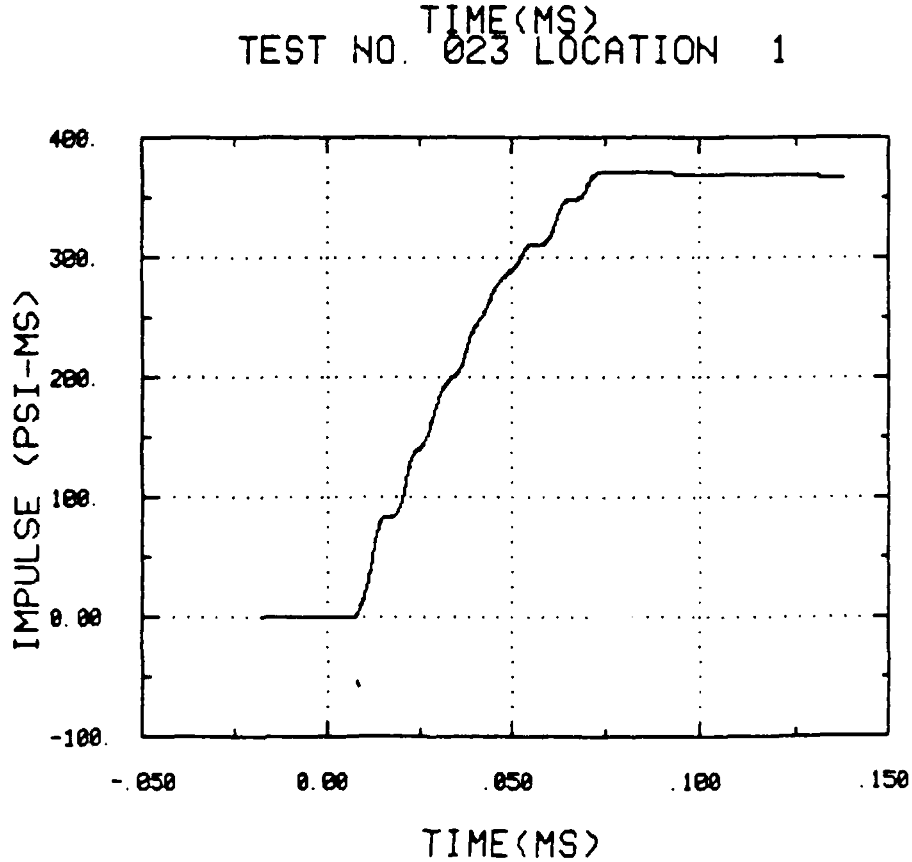


Figure 4. Test no. 23

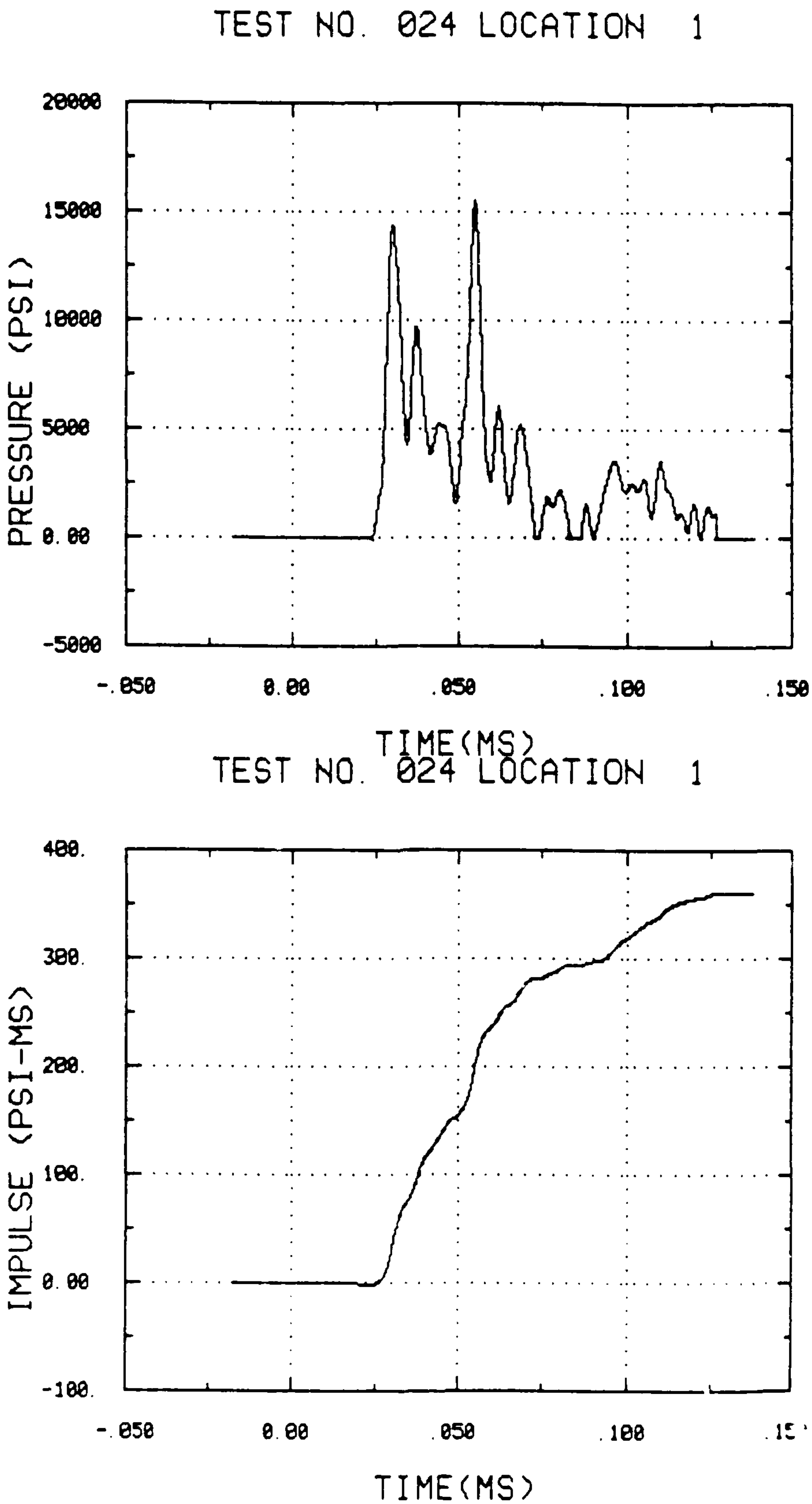


Figure 5. Test no. 24

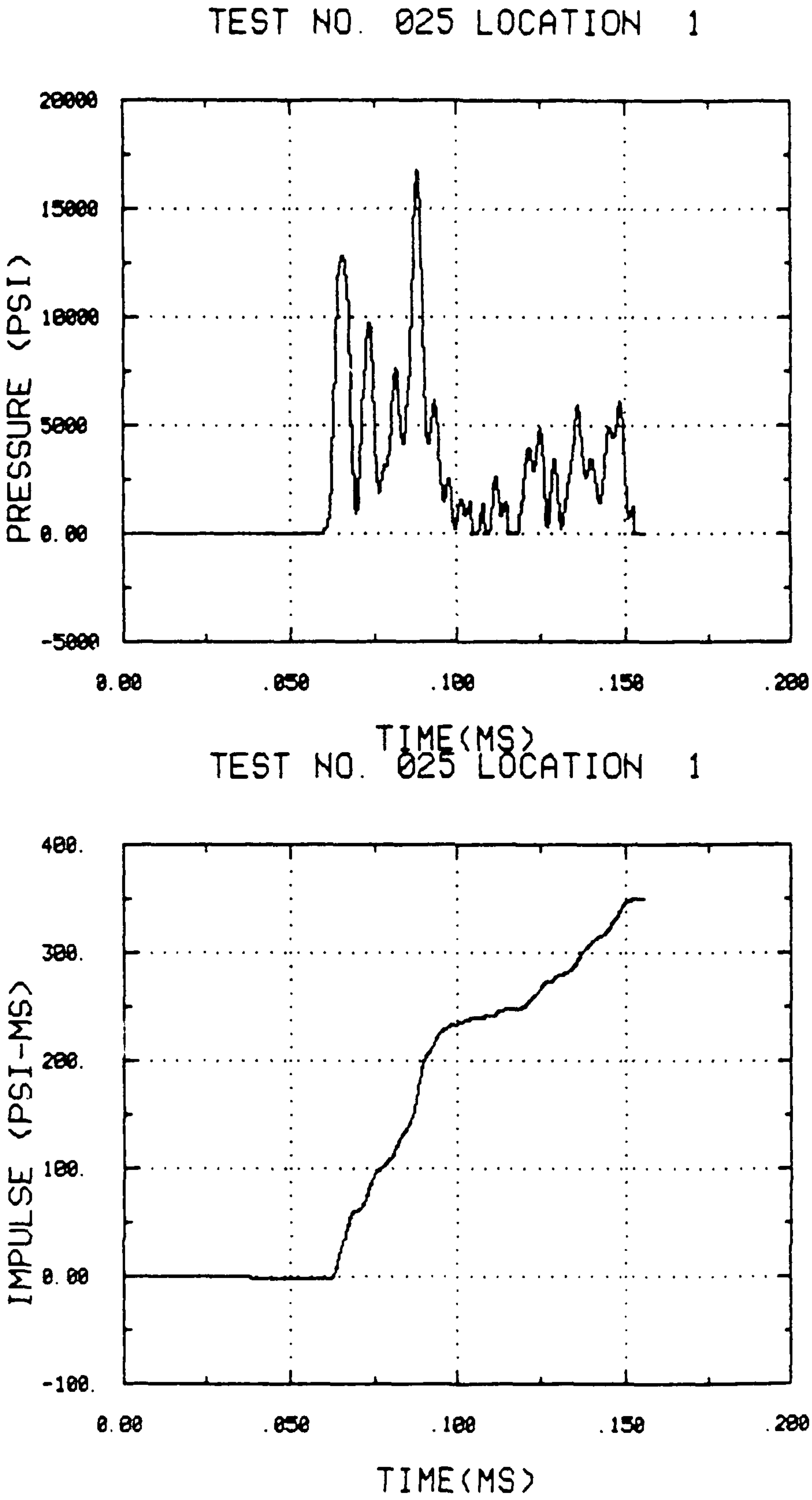


Figure 6. Test no. 25

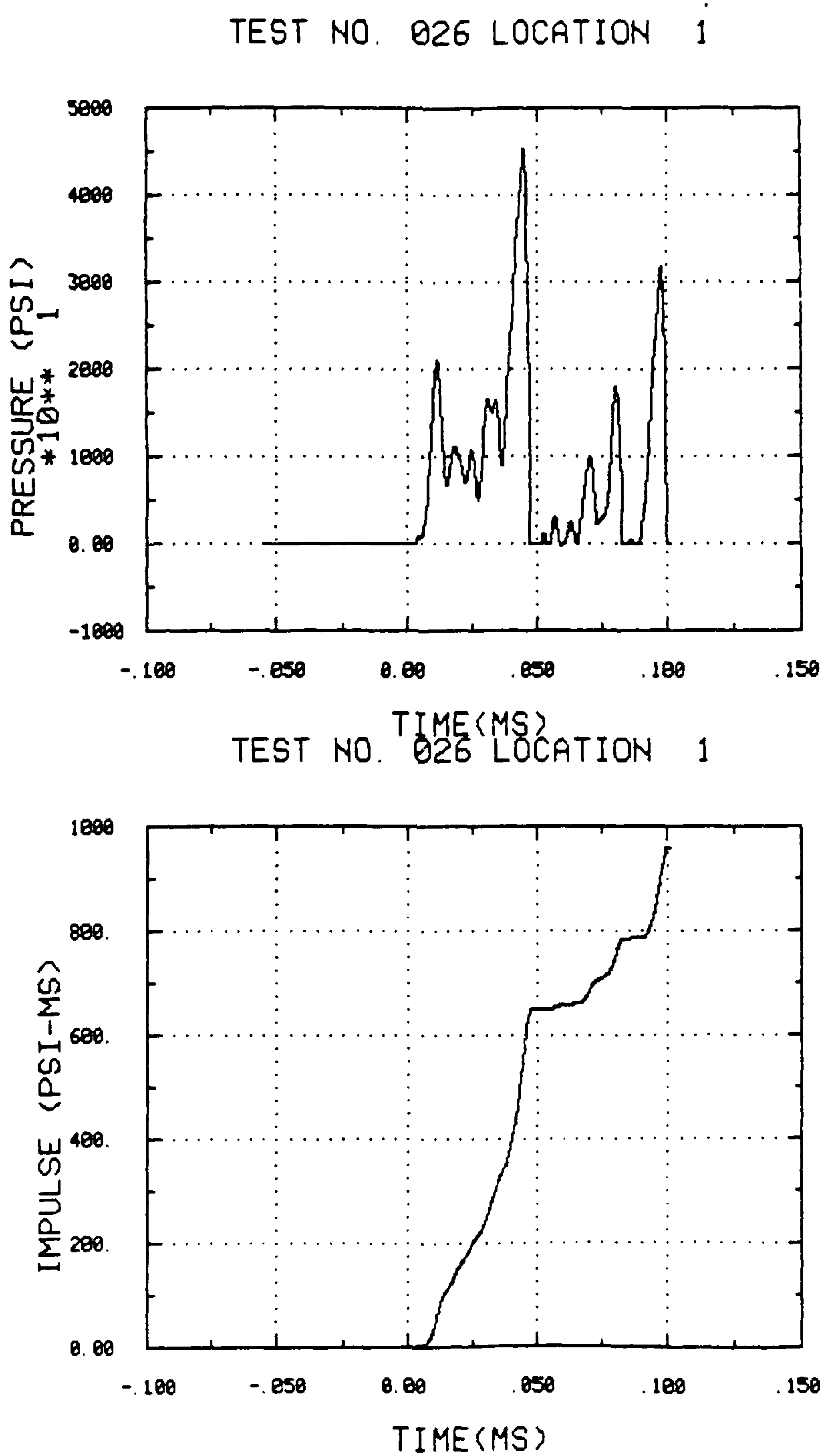
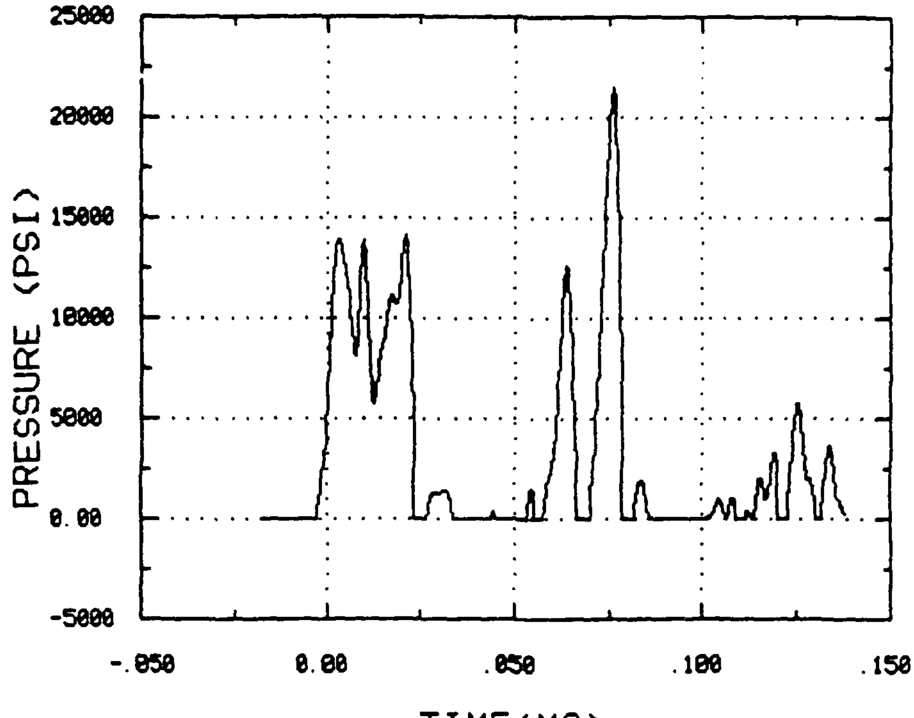


Figure 7. Test no. 26

TEST NO. 027 LOCATION 1



TEST NO. 027 LOCATION 1

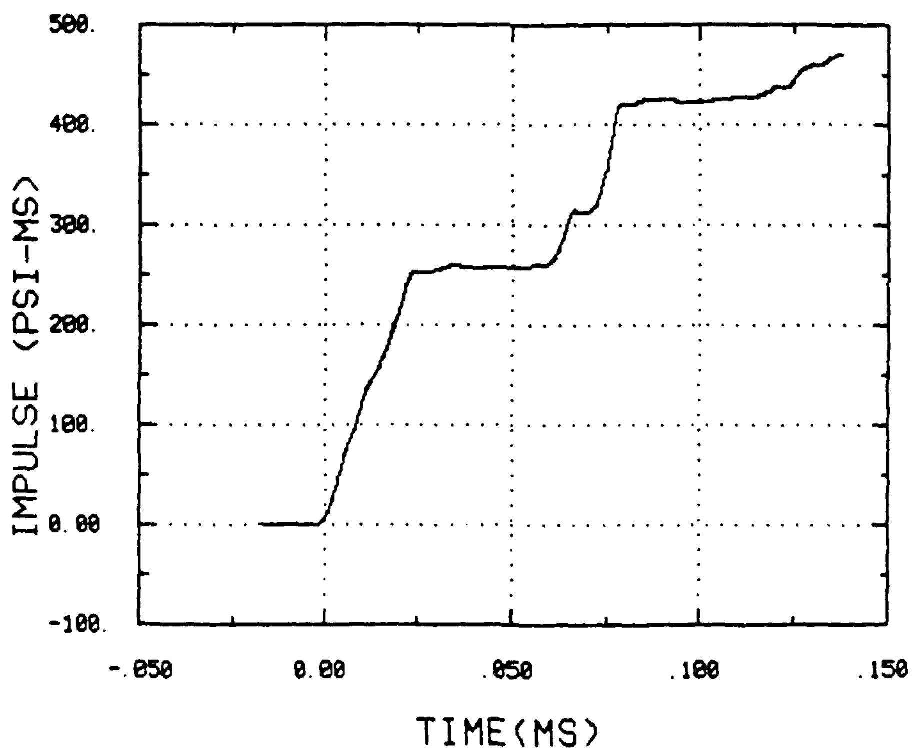
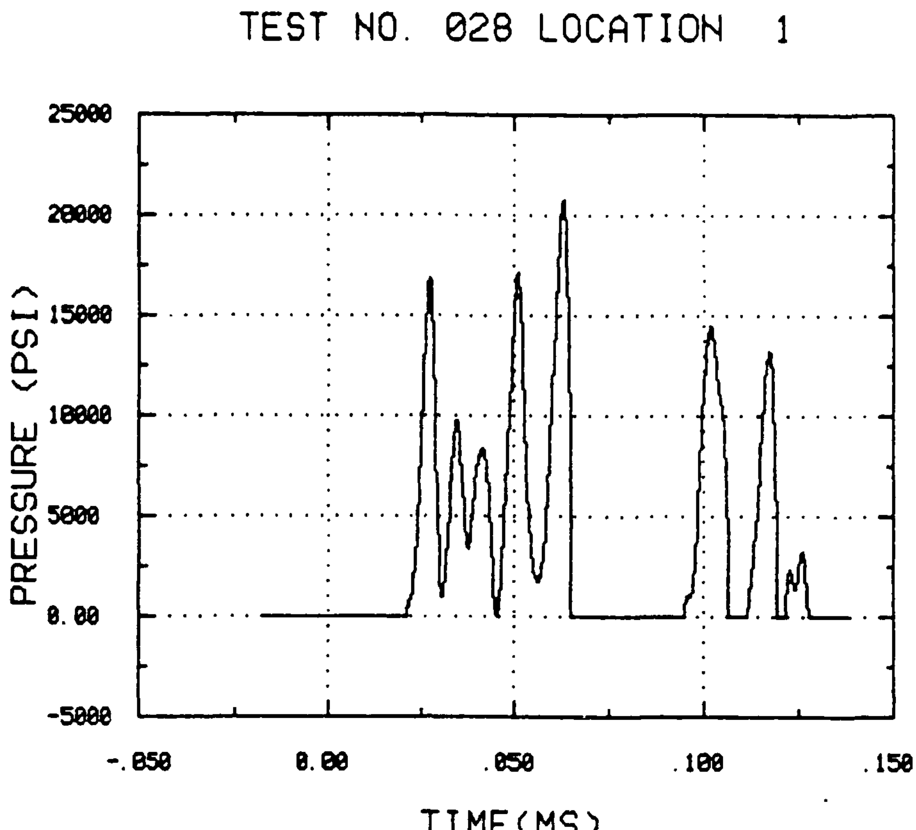


Figure 8. Test no. 27



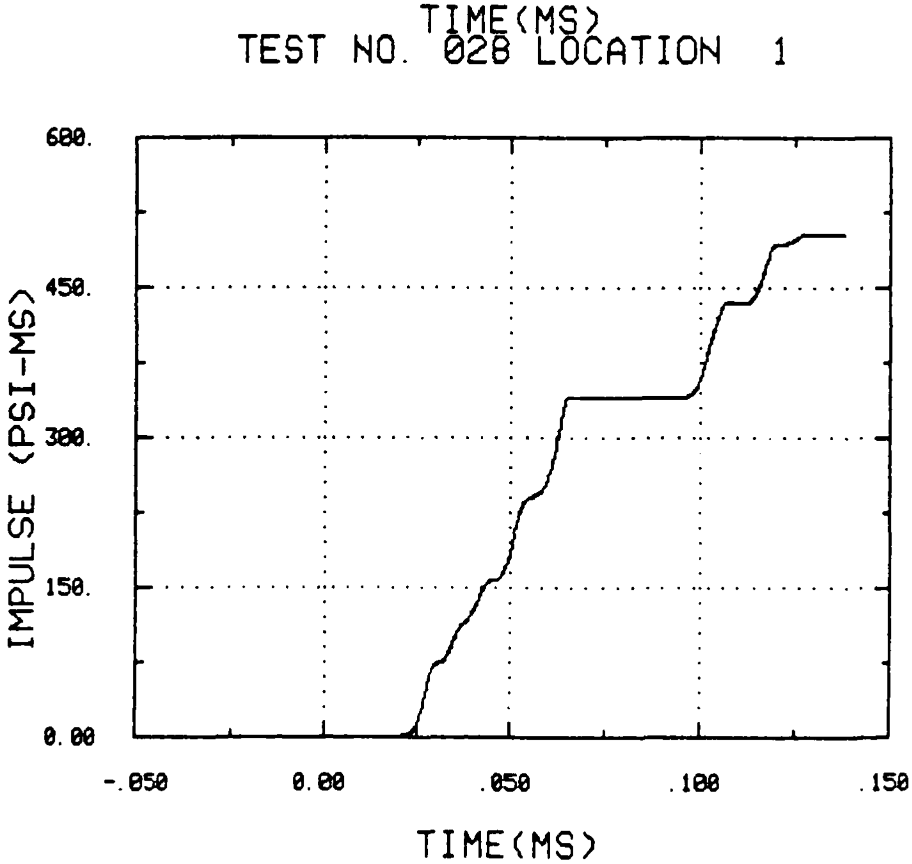


Figure 9. Test no. 28

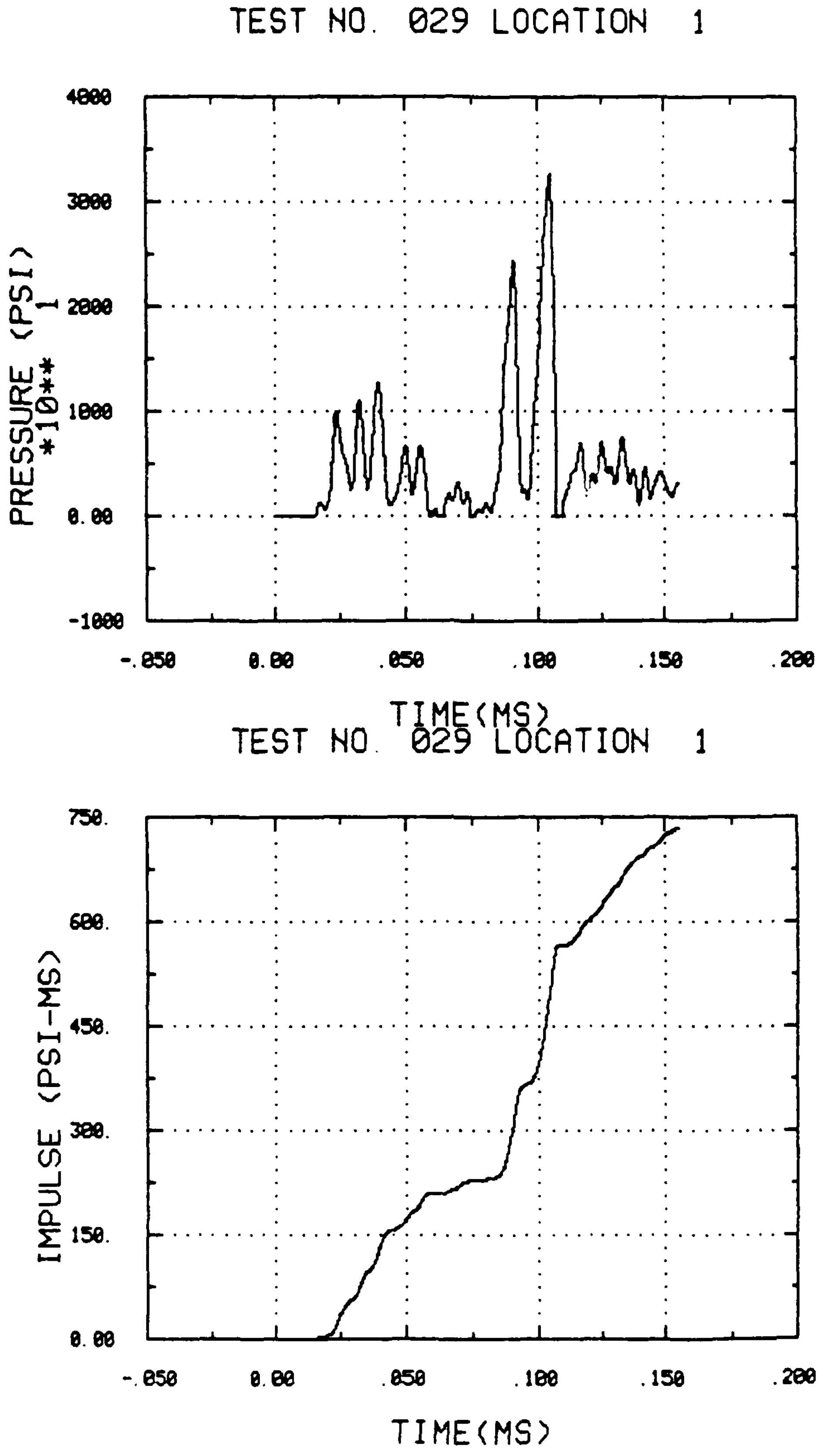
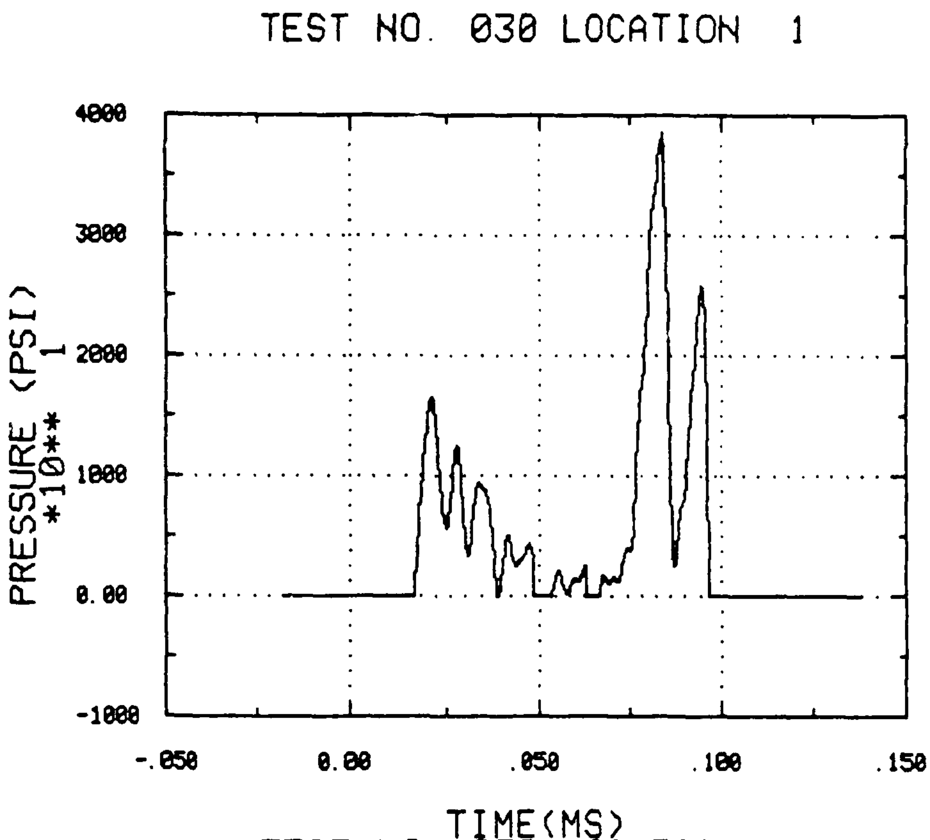


Figure 10. Test no. 29



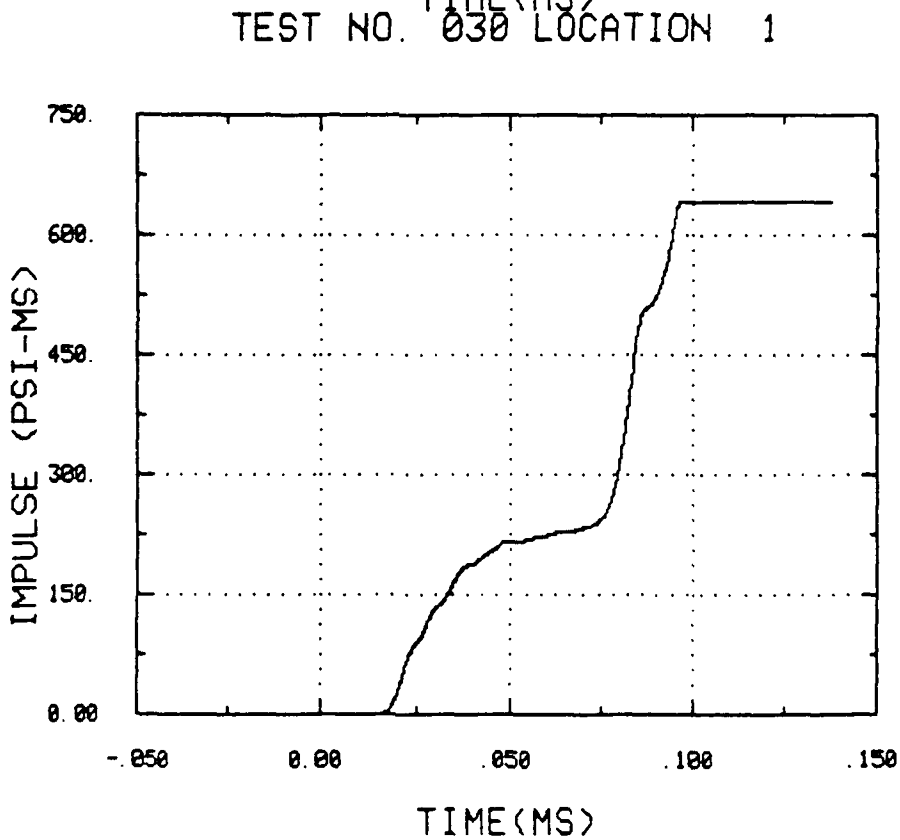
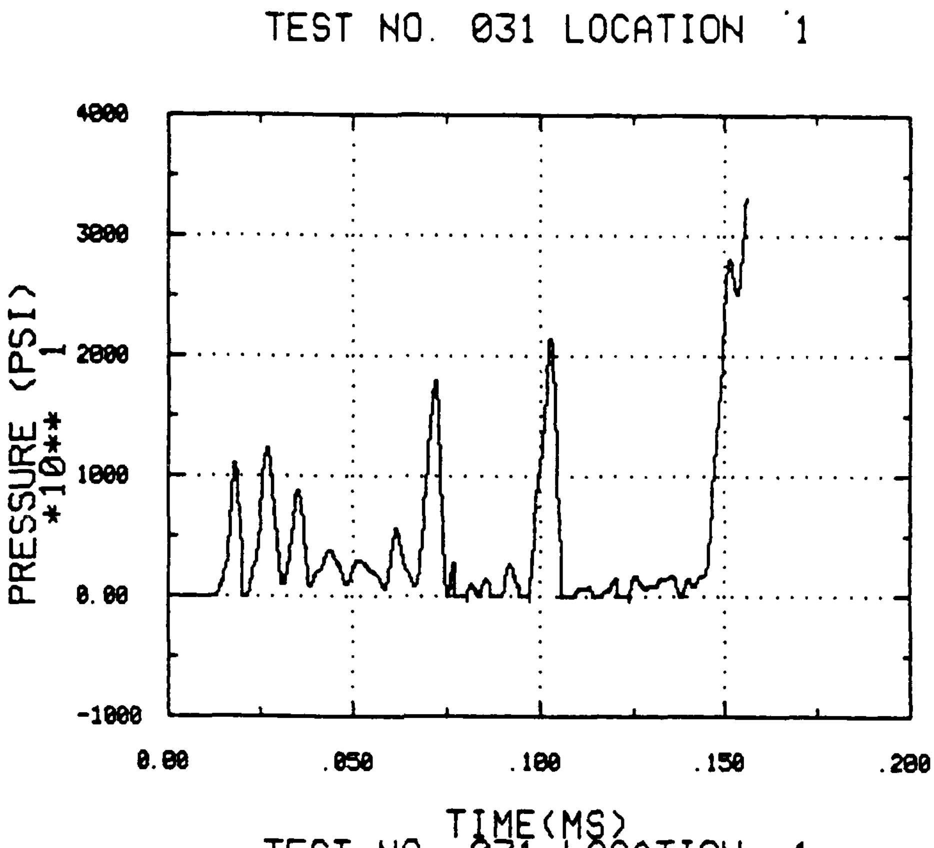


Figure 11. Test no. 30



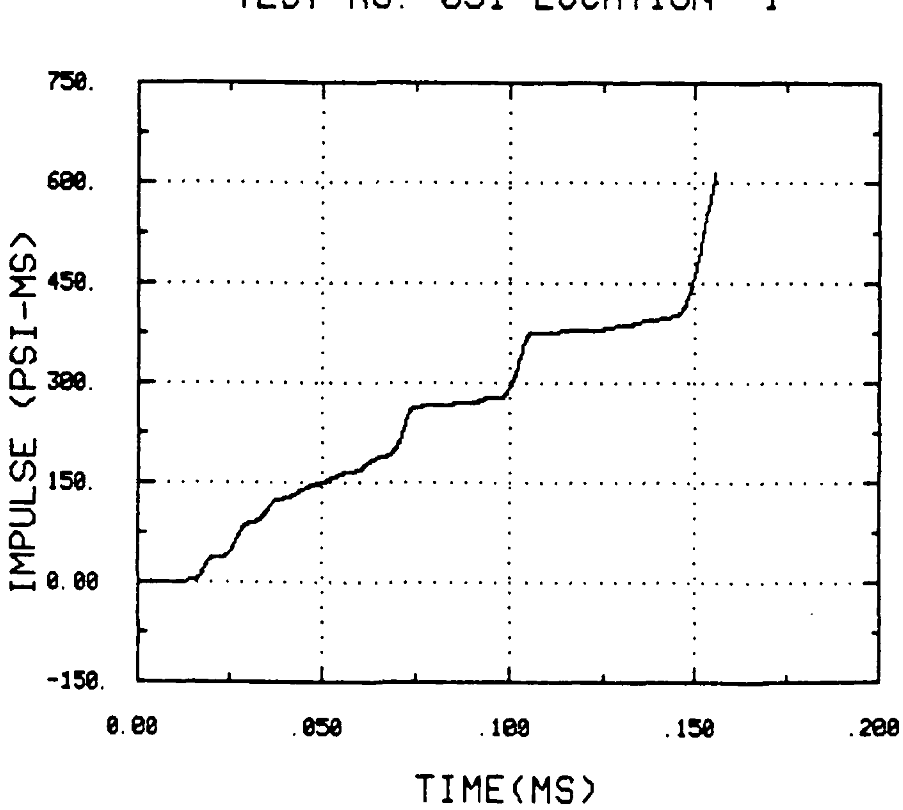


Figure 12. Test no. 31

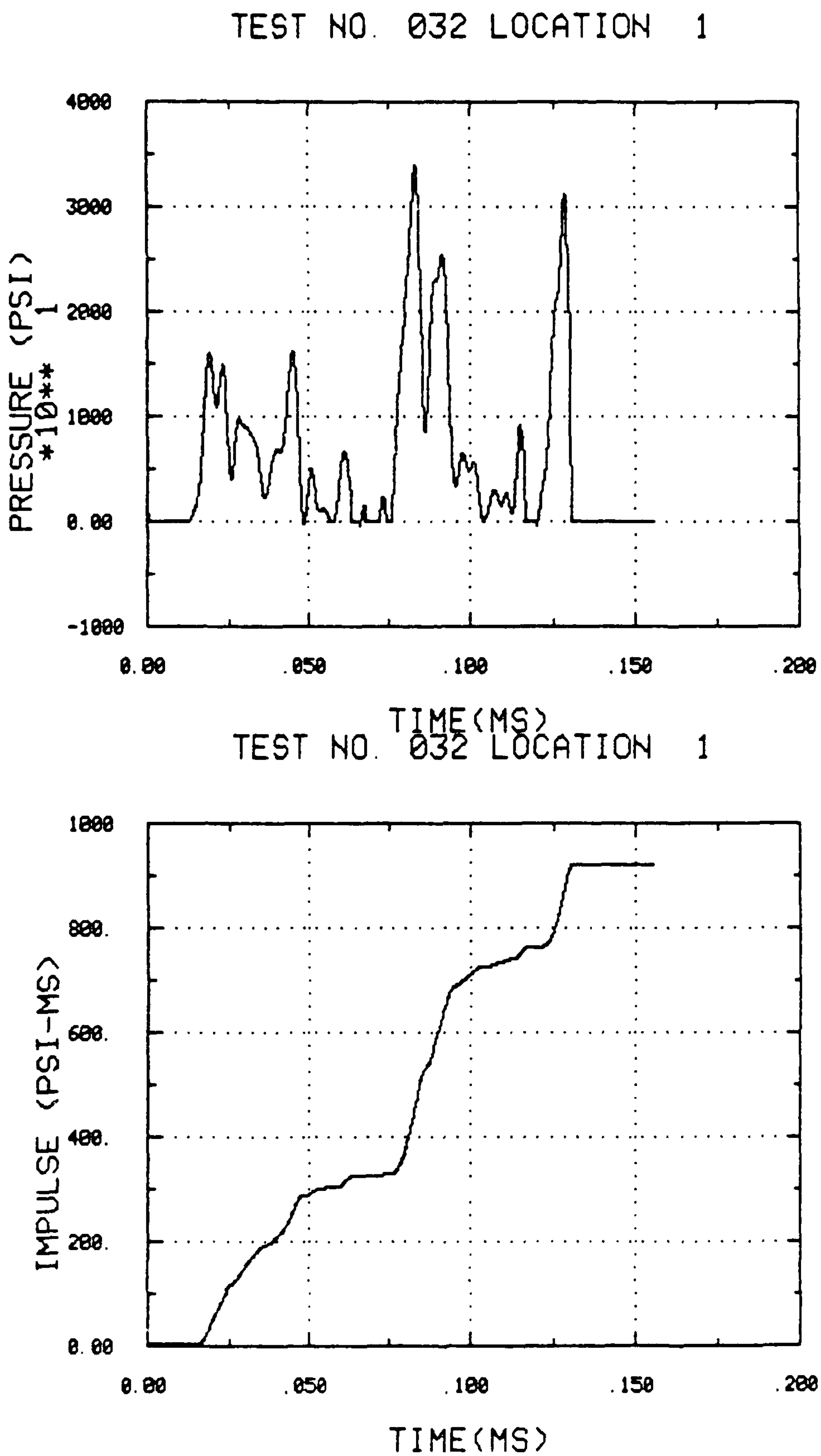
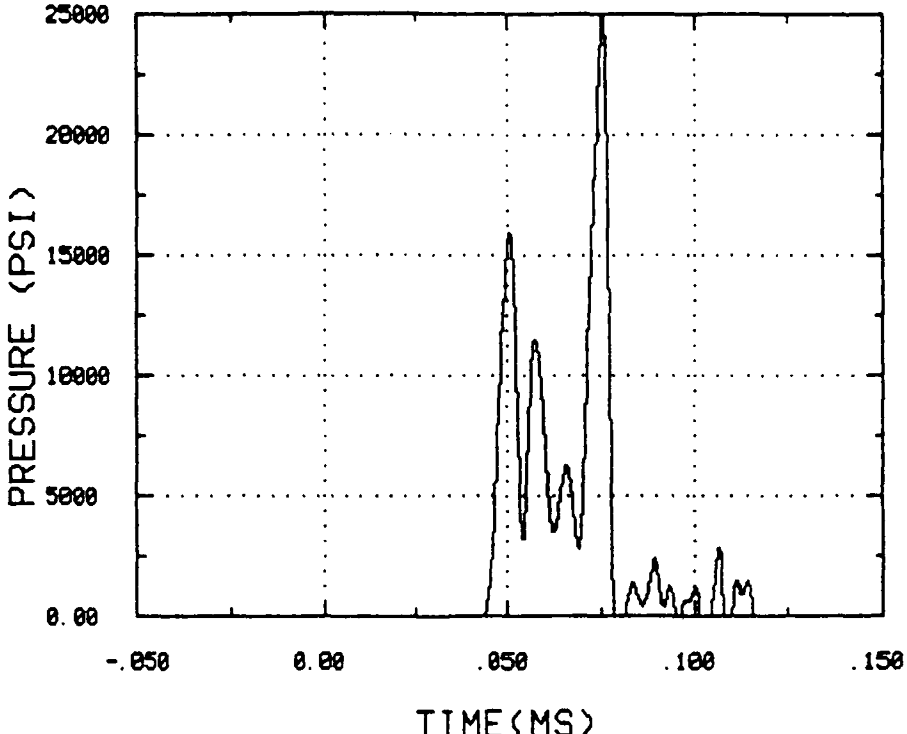


Figure 13. Test no. 32

TEST NO. 033 LOCATION 1



TEST NO. 033 LOCATION 1

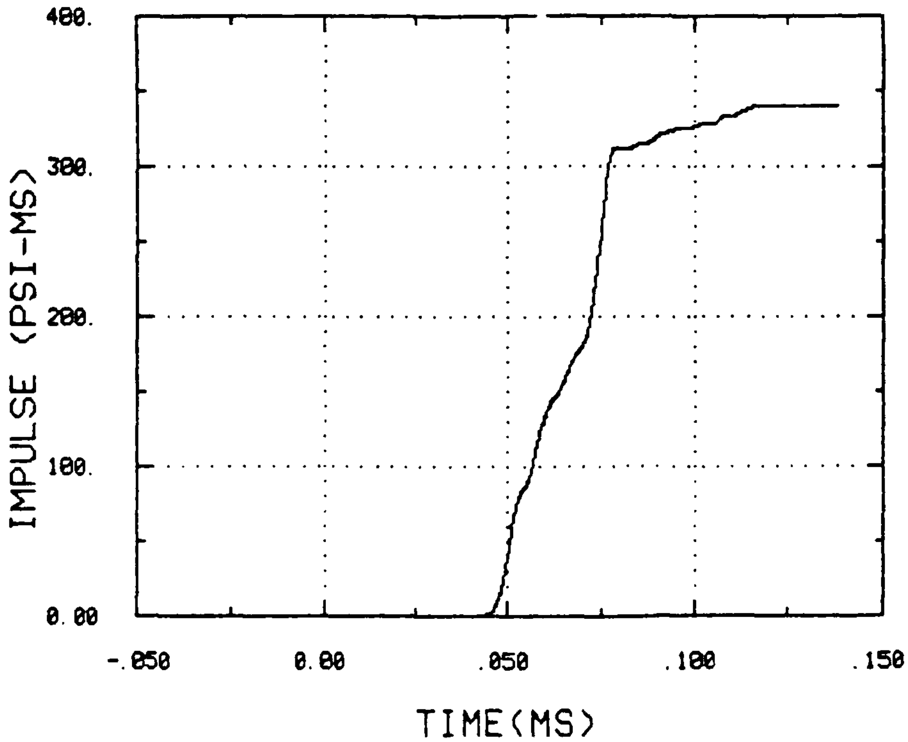
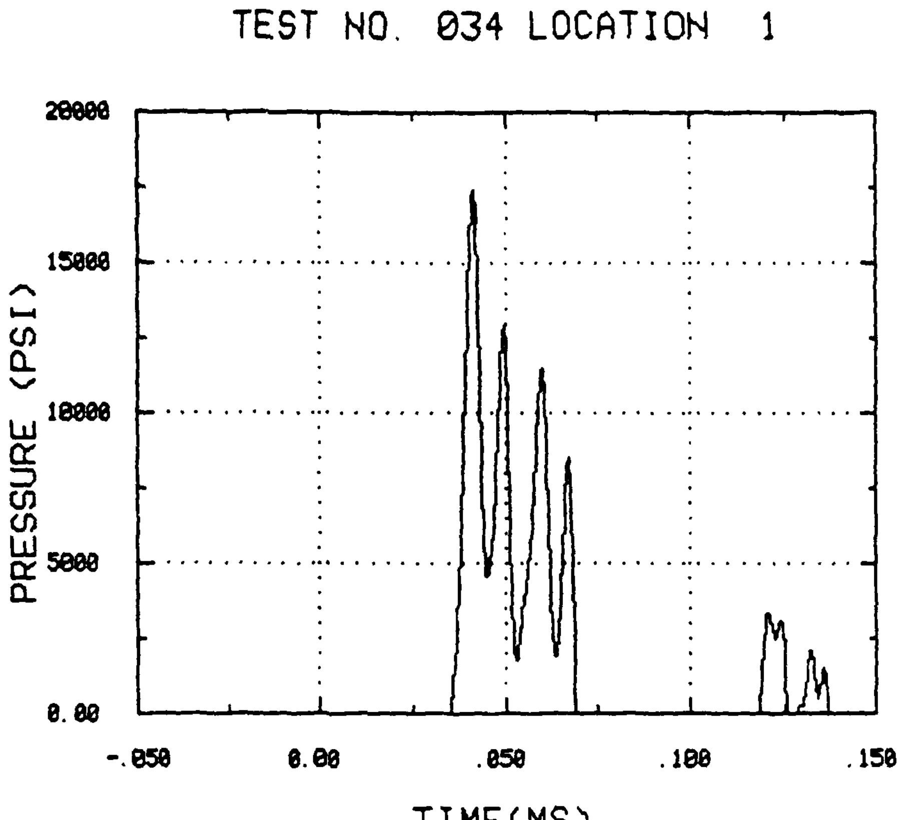


Figure 14. Test no. 33



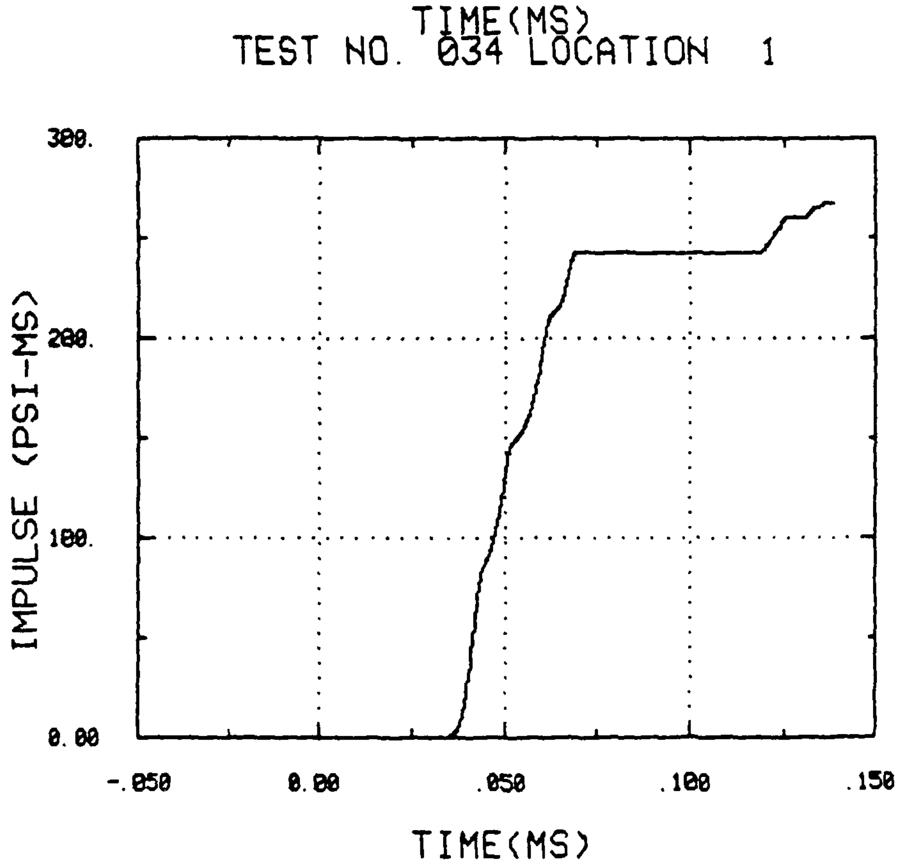


Figure 15. Test no. 34

NOTE: Lid deformation

Figure 16. Quart container with NOS 365, test no. 34

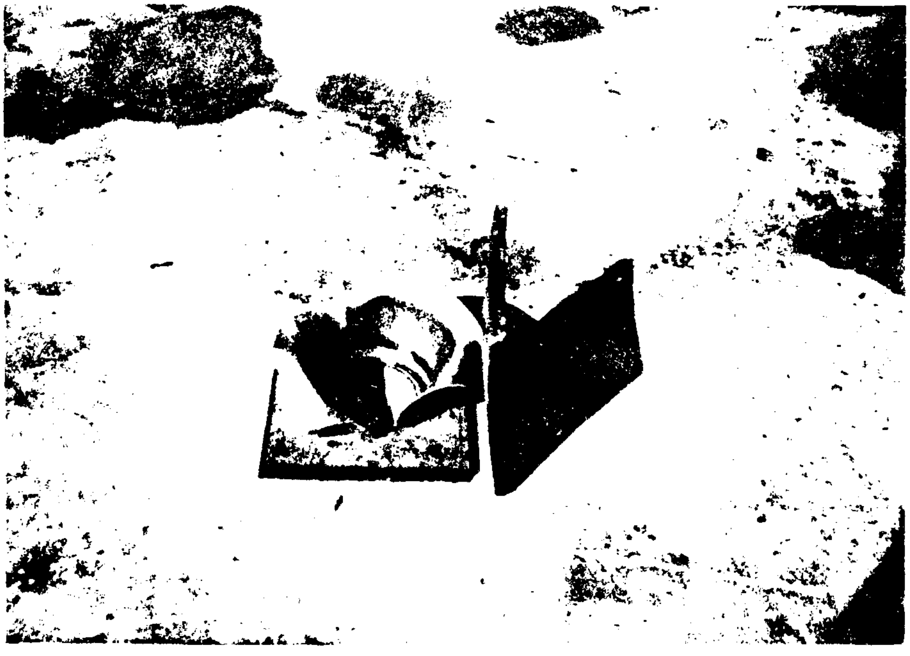


Figure 17. Quart container with NOS 365, test no. 34

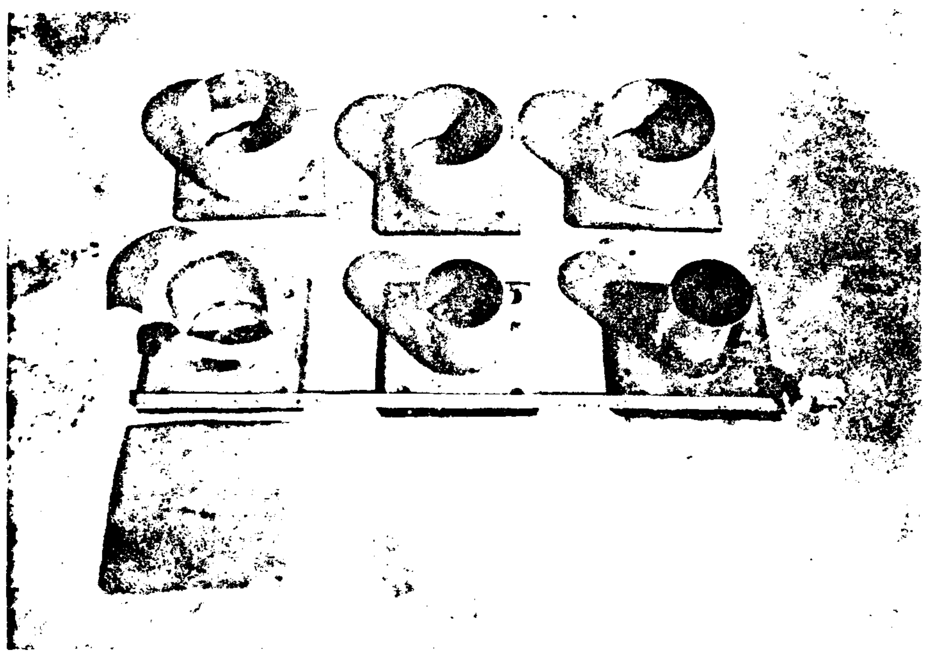
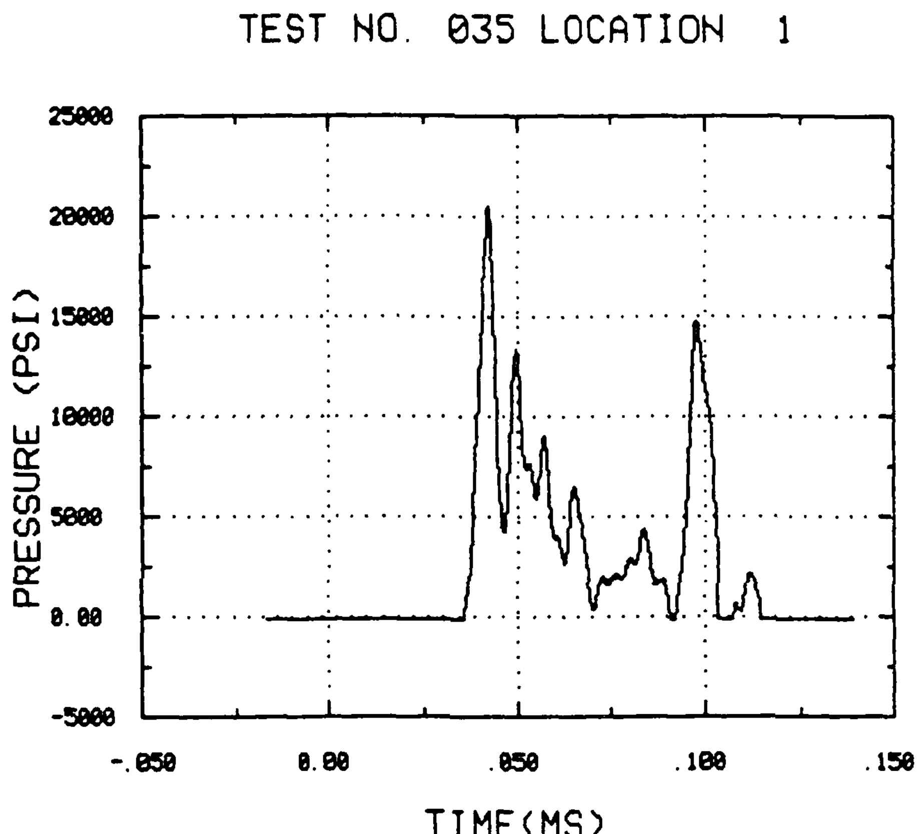


Figure 18. Damage comparison for three 1/2 gal. and 3 quart tests



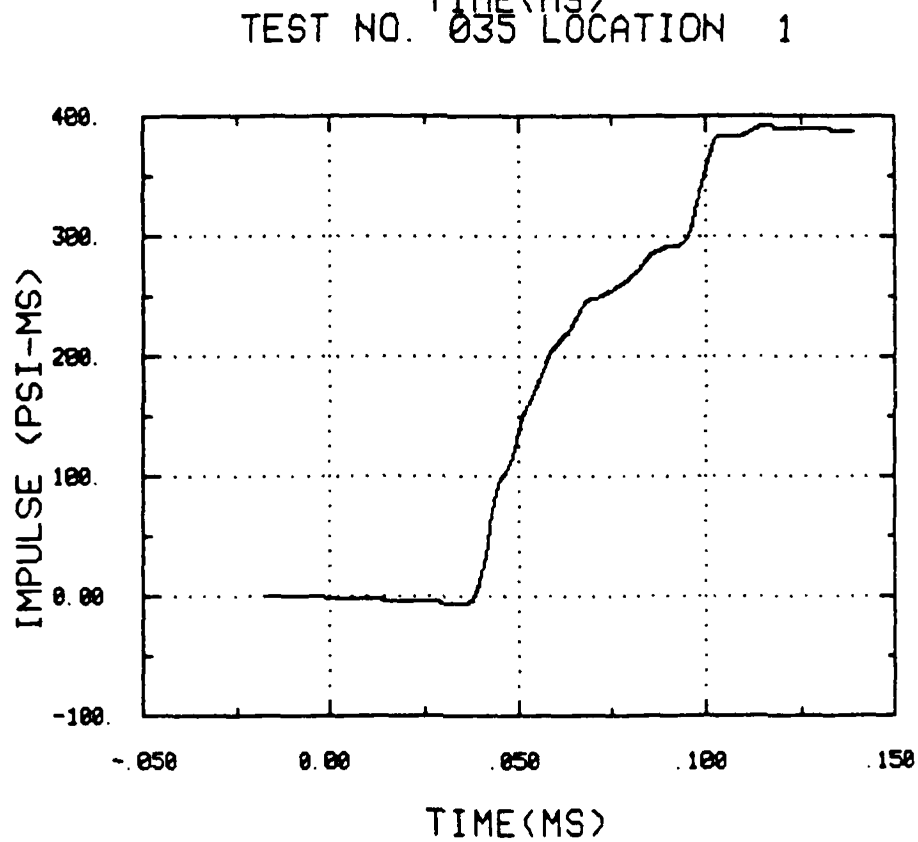
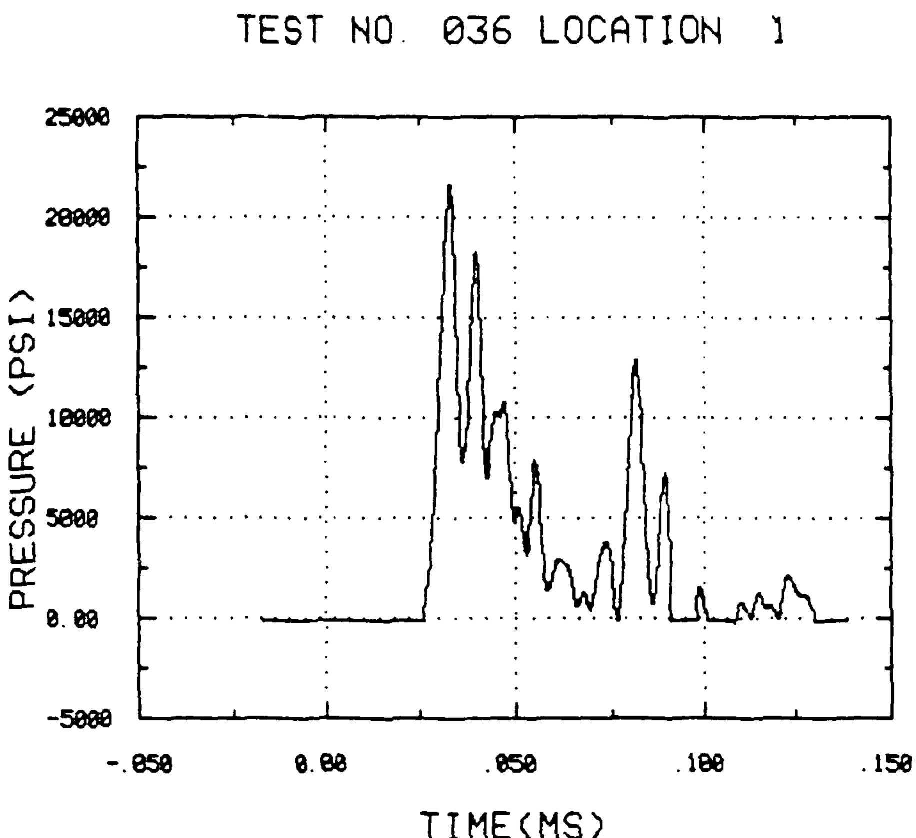


Figure 19. Test no. 35



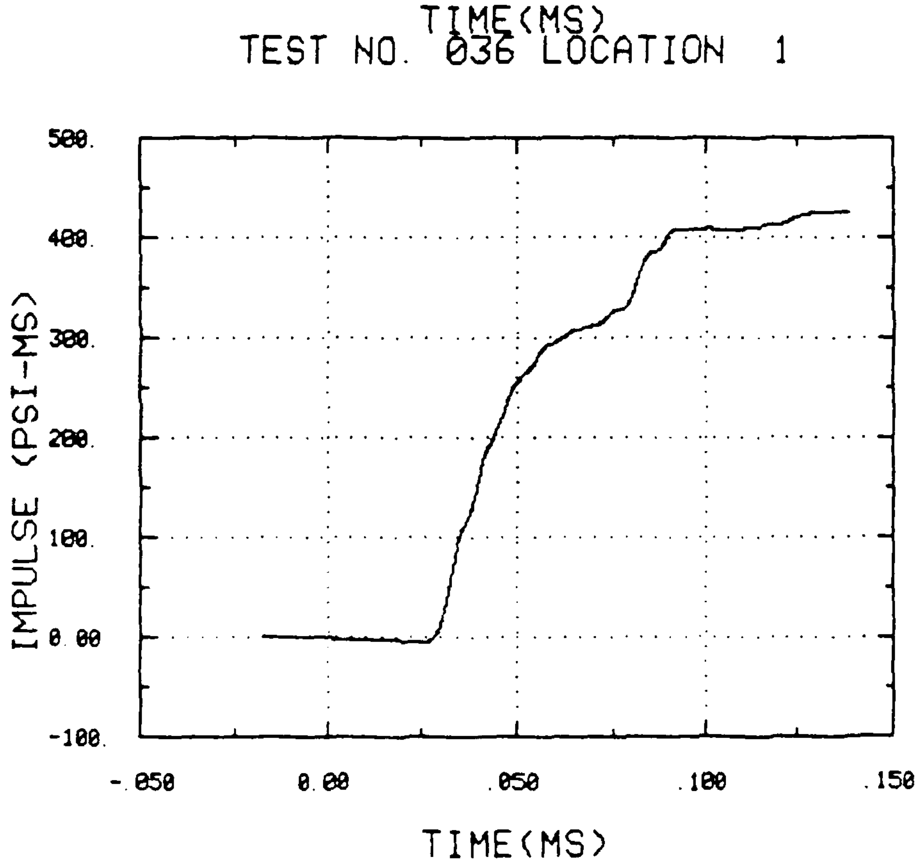
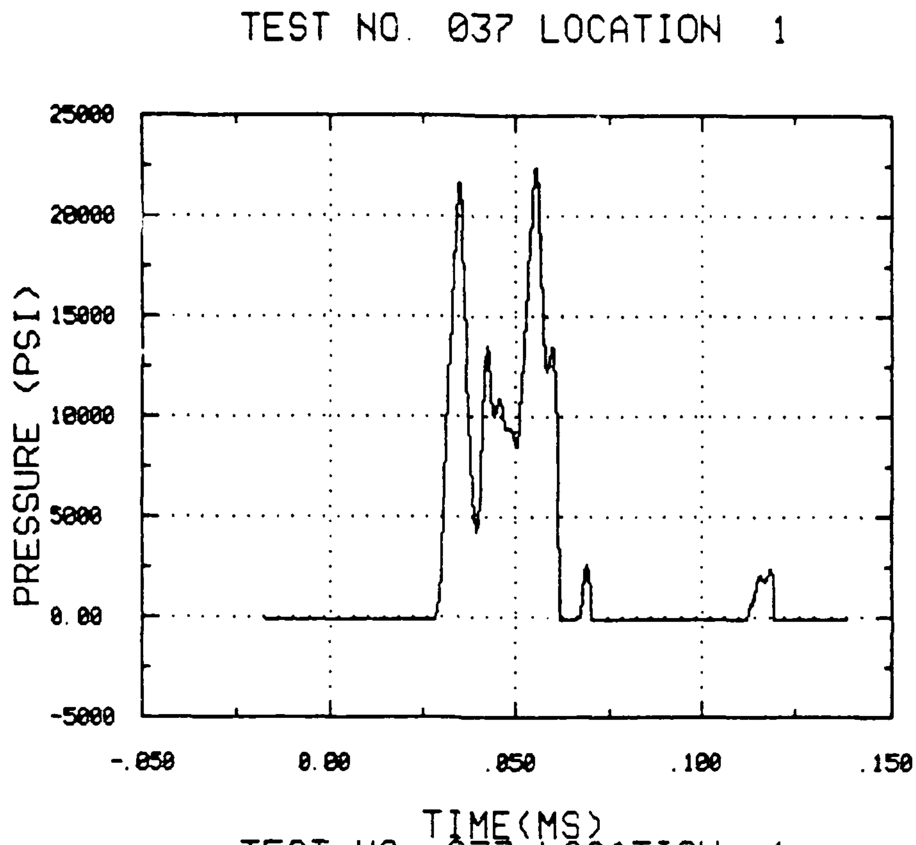


Figure 20. Test no. 36



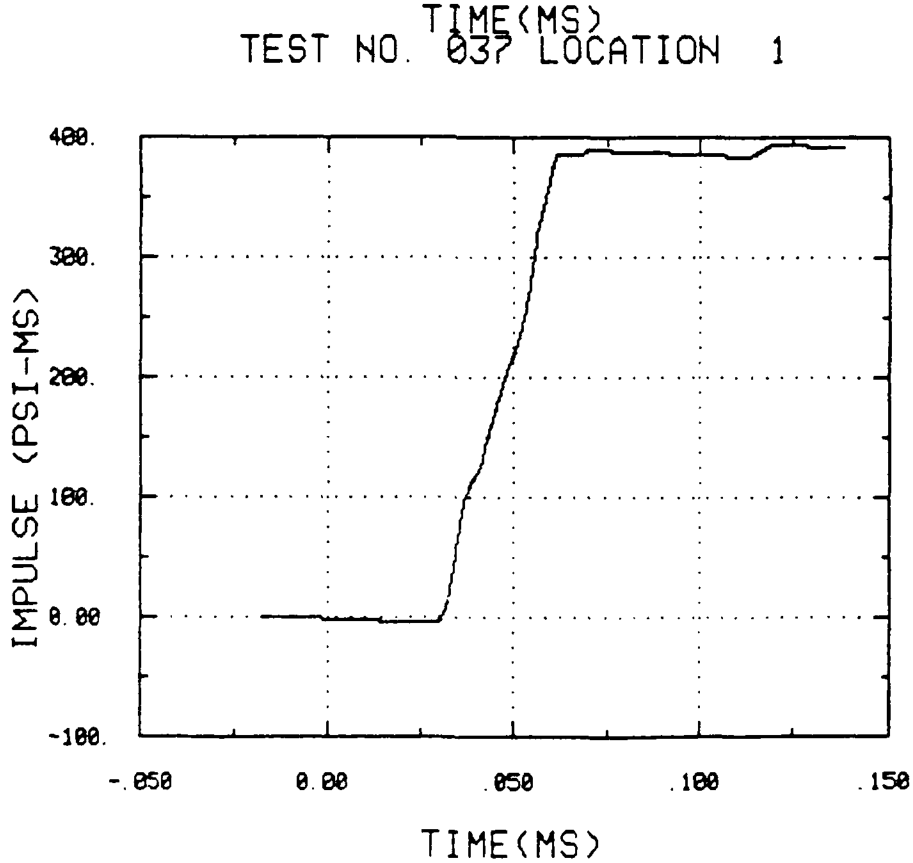
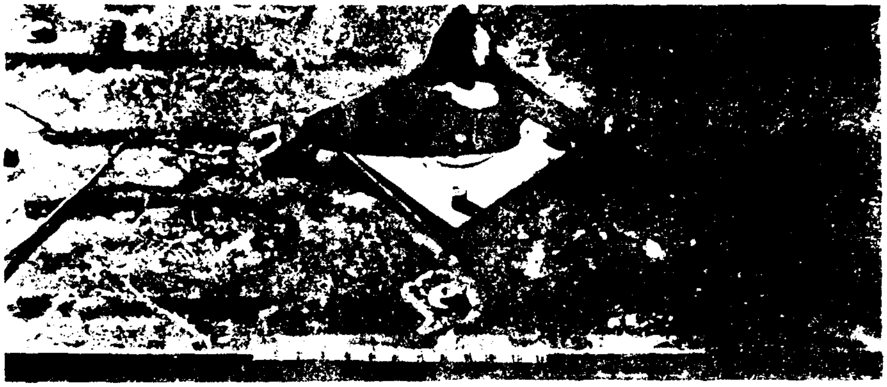


Figure 21. Test no. 37



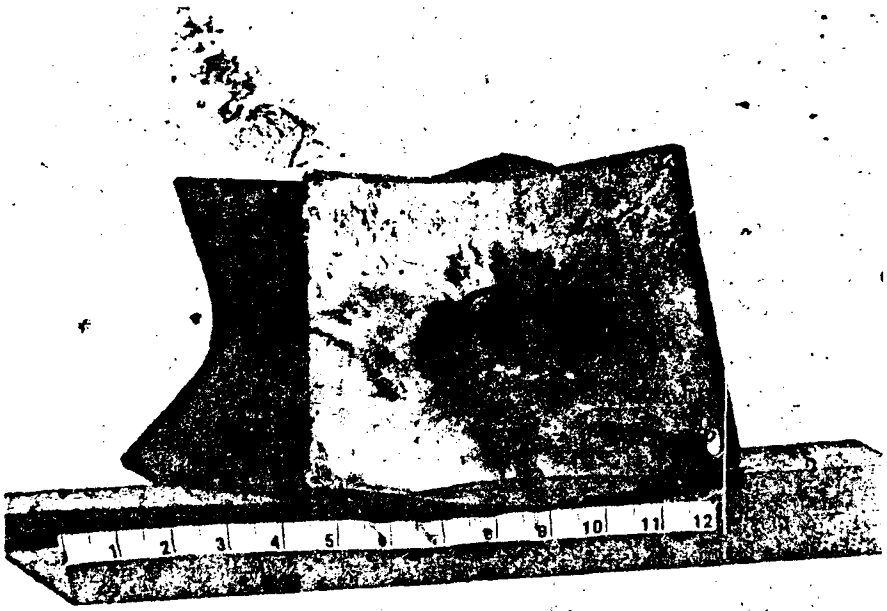


Figure 22. Container baseplate and witness plate for test no, 38

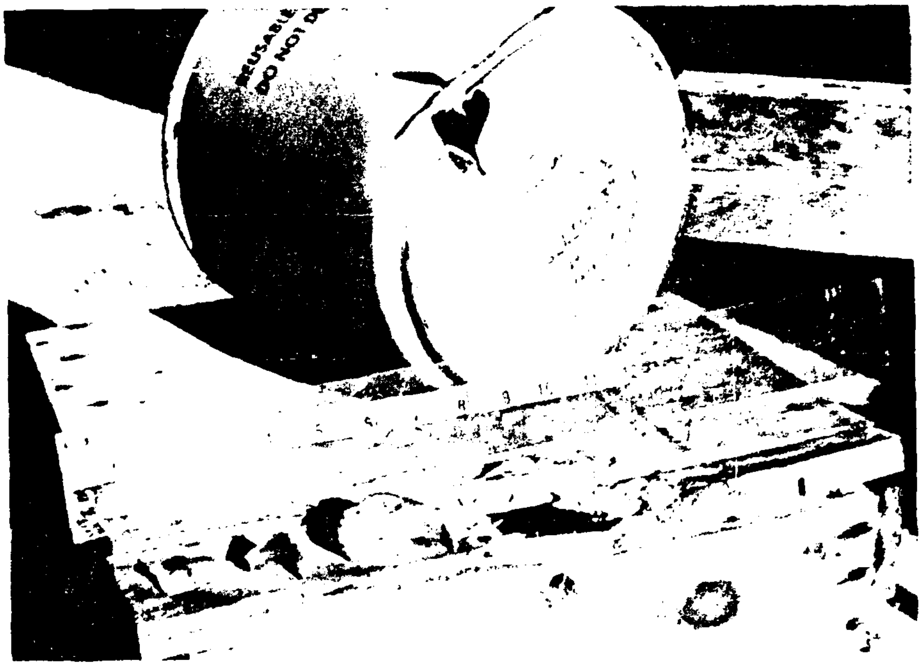
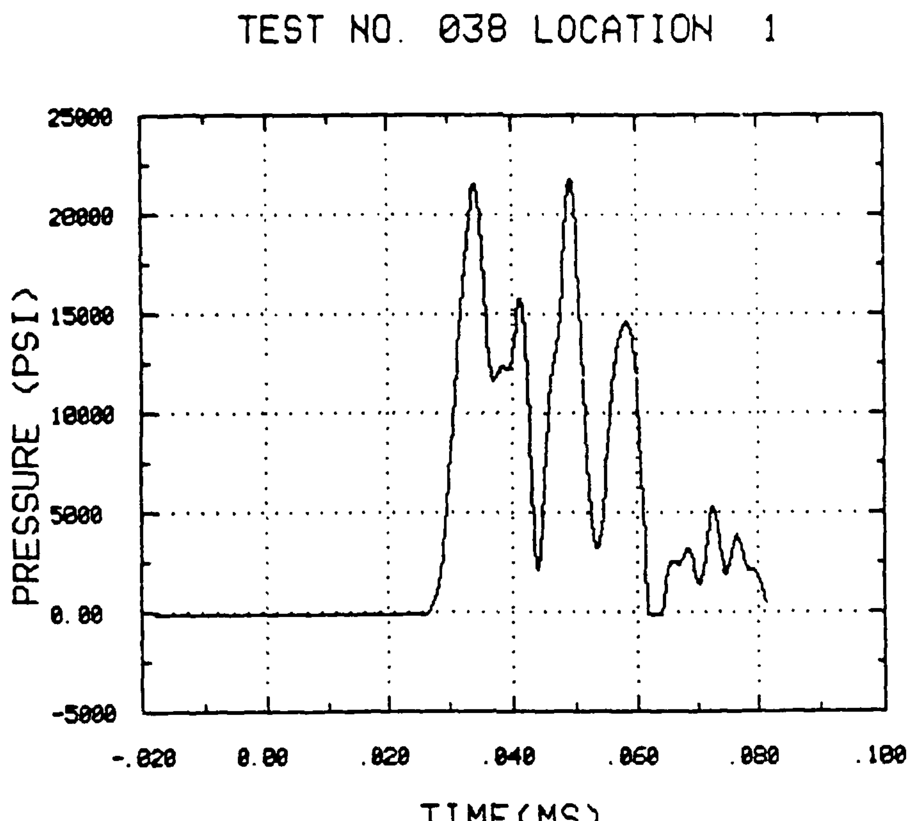


Figure 23. Canister sidewall fragments for test no. 38

Figure 24. Fragment damage to woolen box, test no. 38



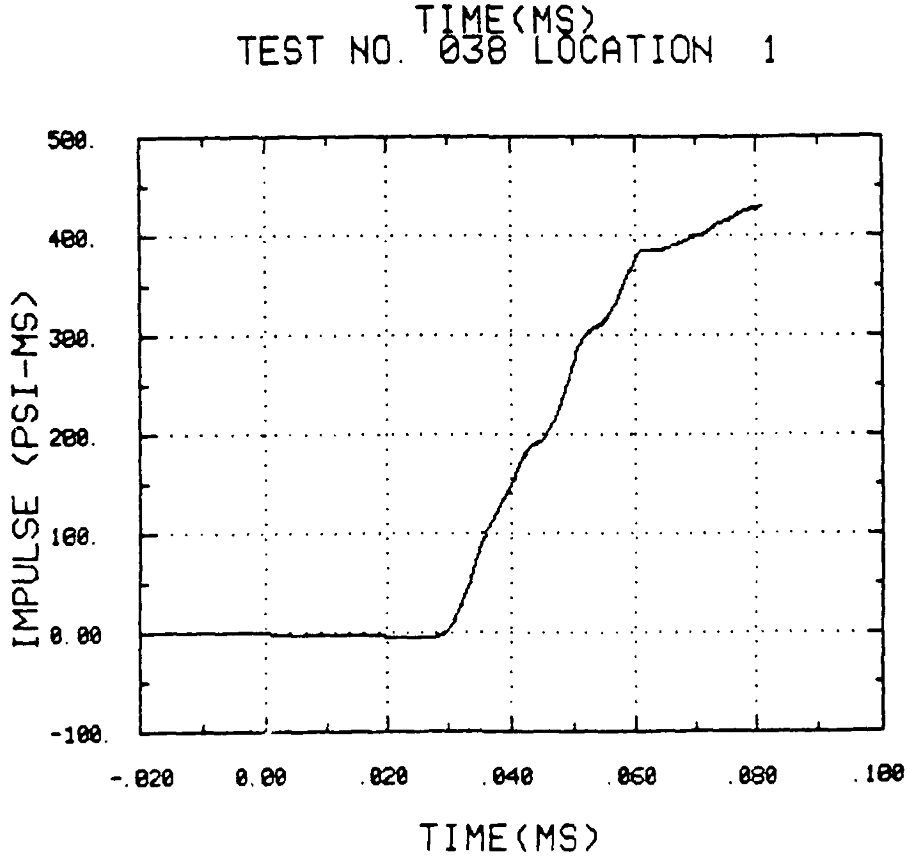


Figure 25. Test no. 38

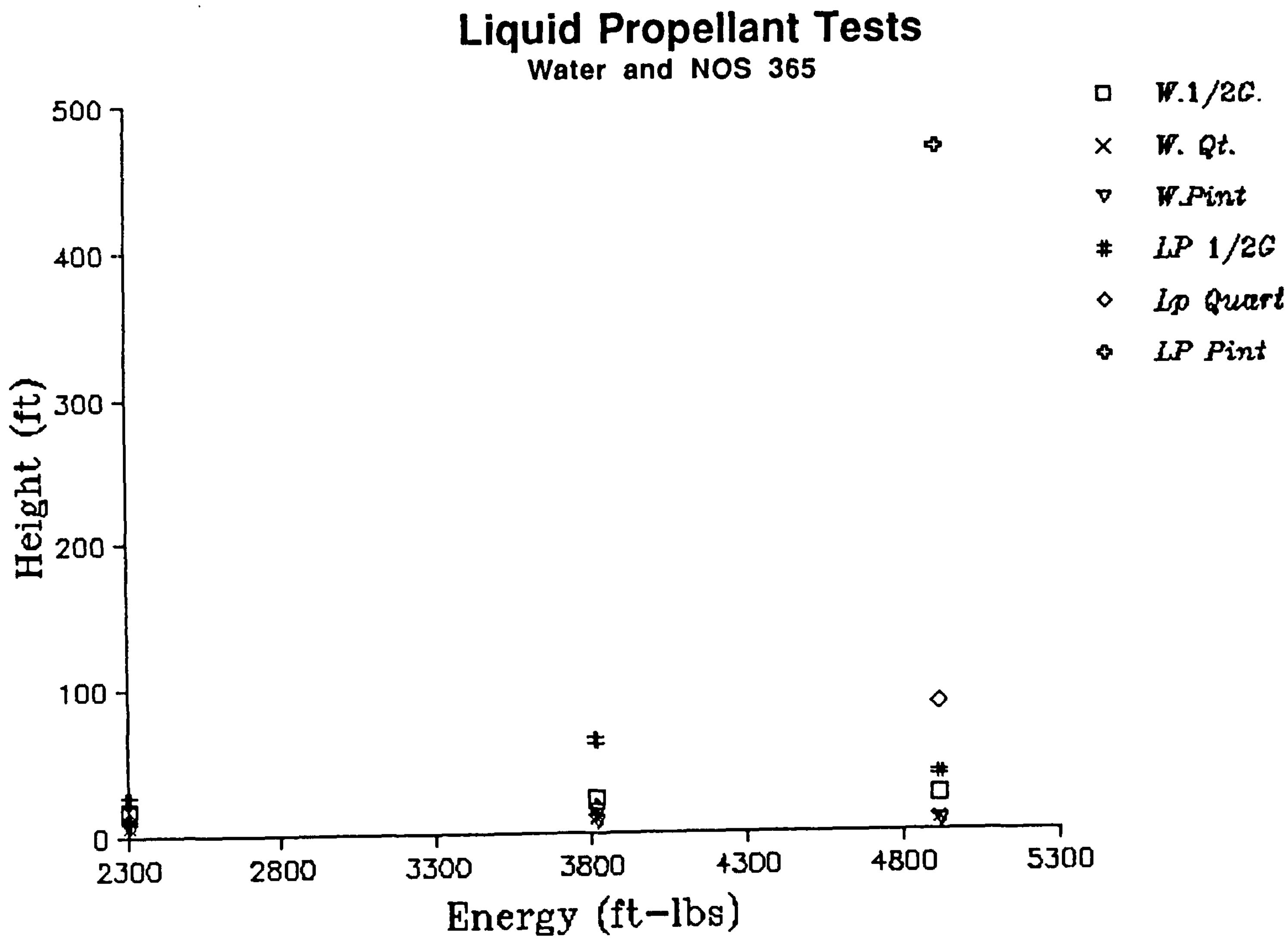


Figure 26. Height versus energy for all tests

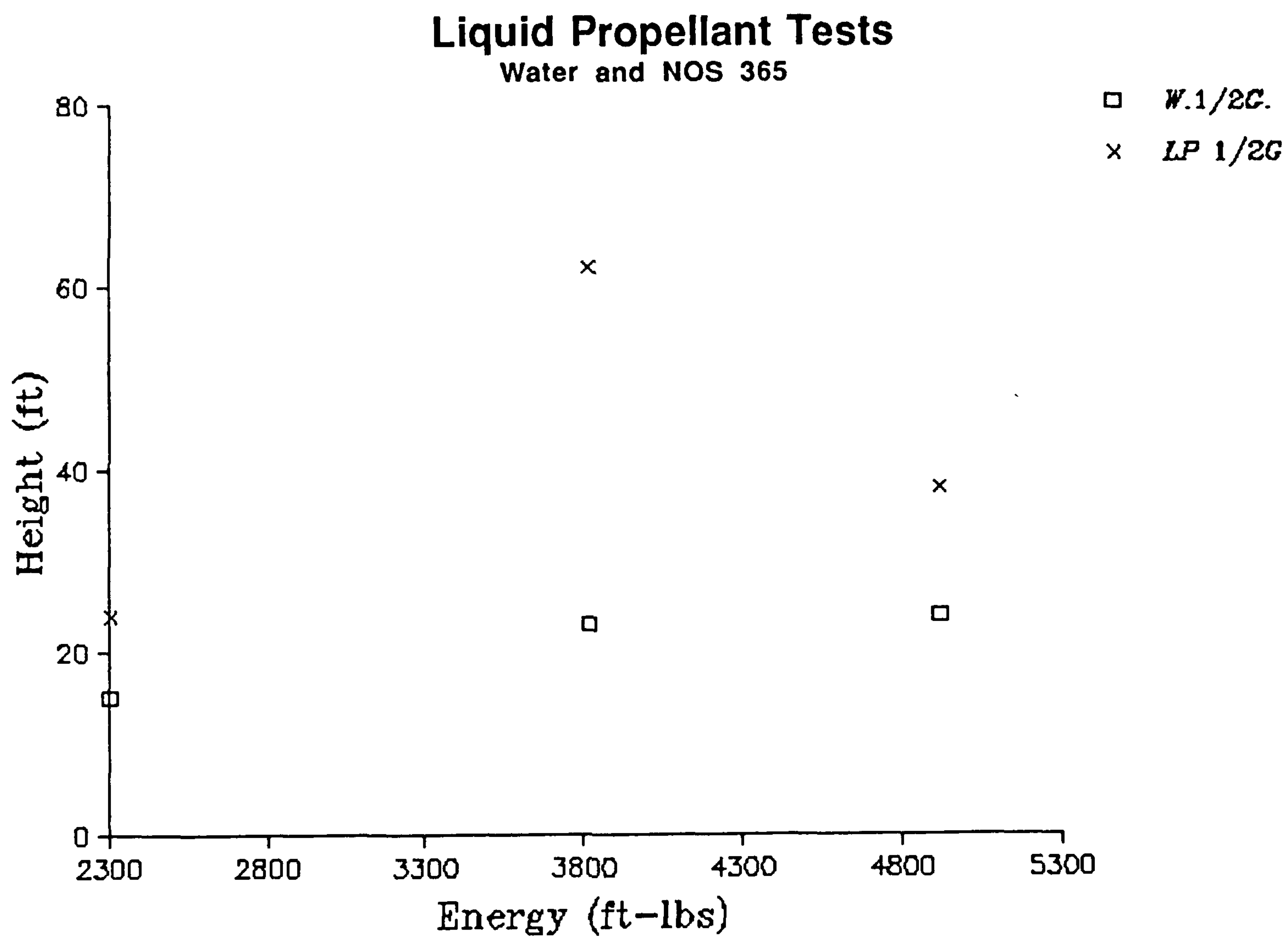


Figure 27. Witness plate height versus energy for 1/2 gallon containers

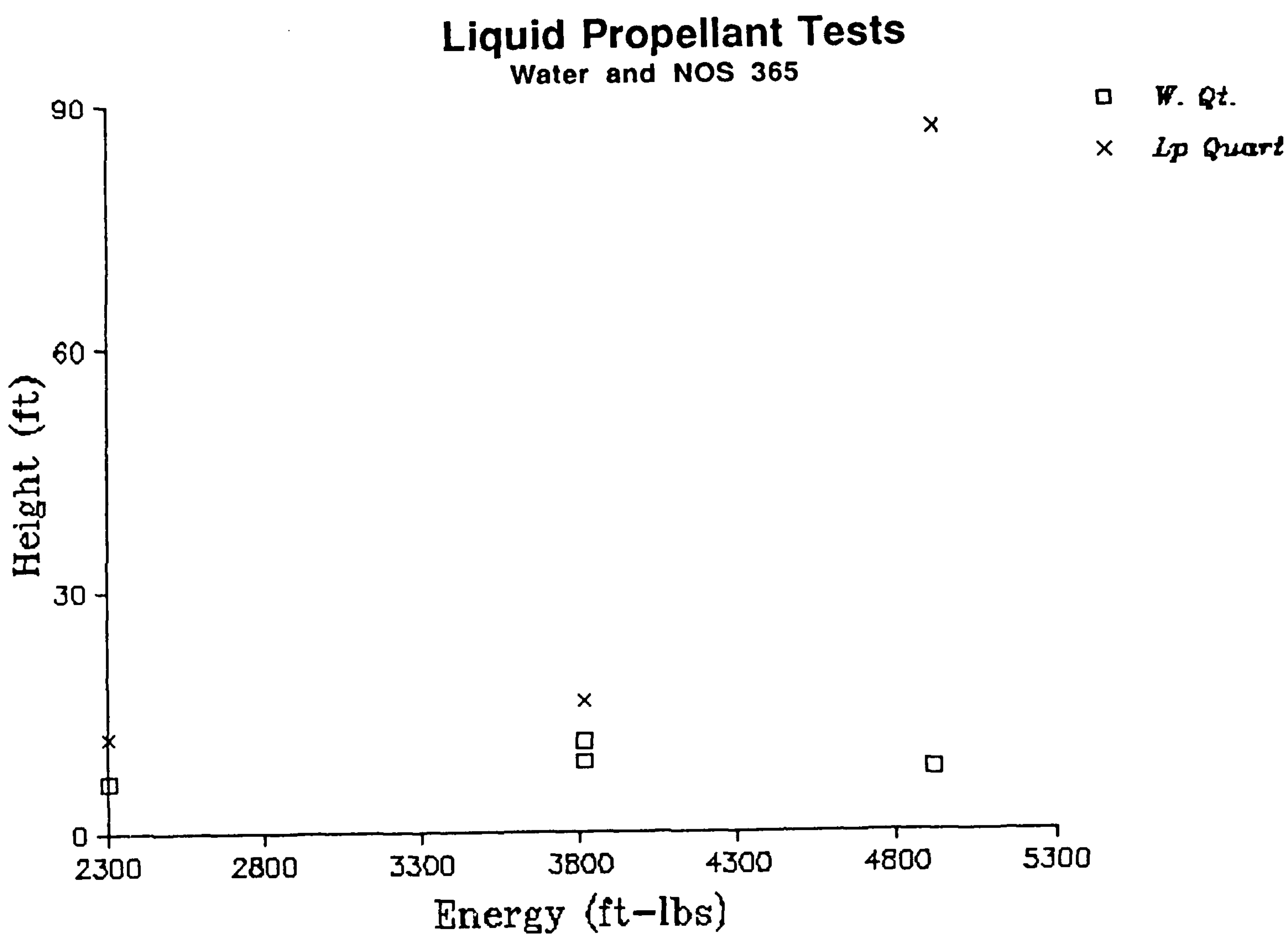


Figure 28. Witness plate height versus energy for quart containers

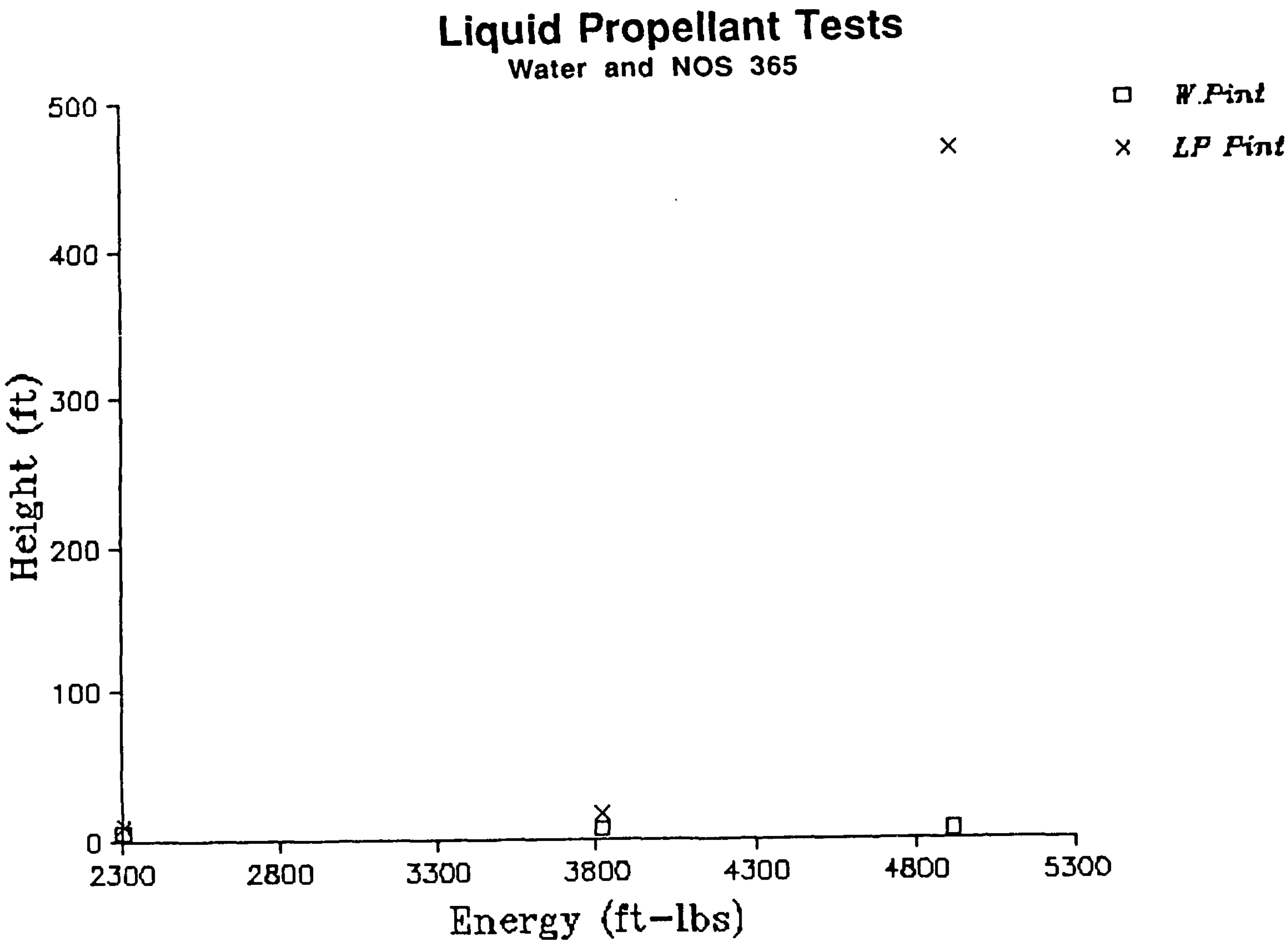


Figure 29. Witness plate height versus energy for pint containers

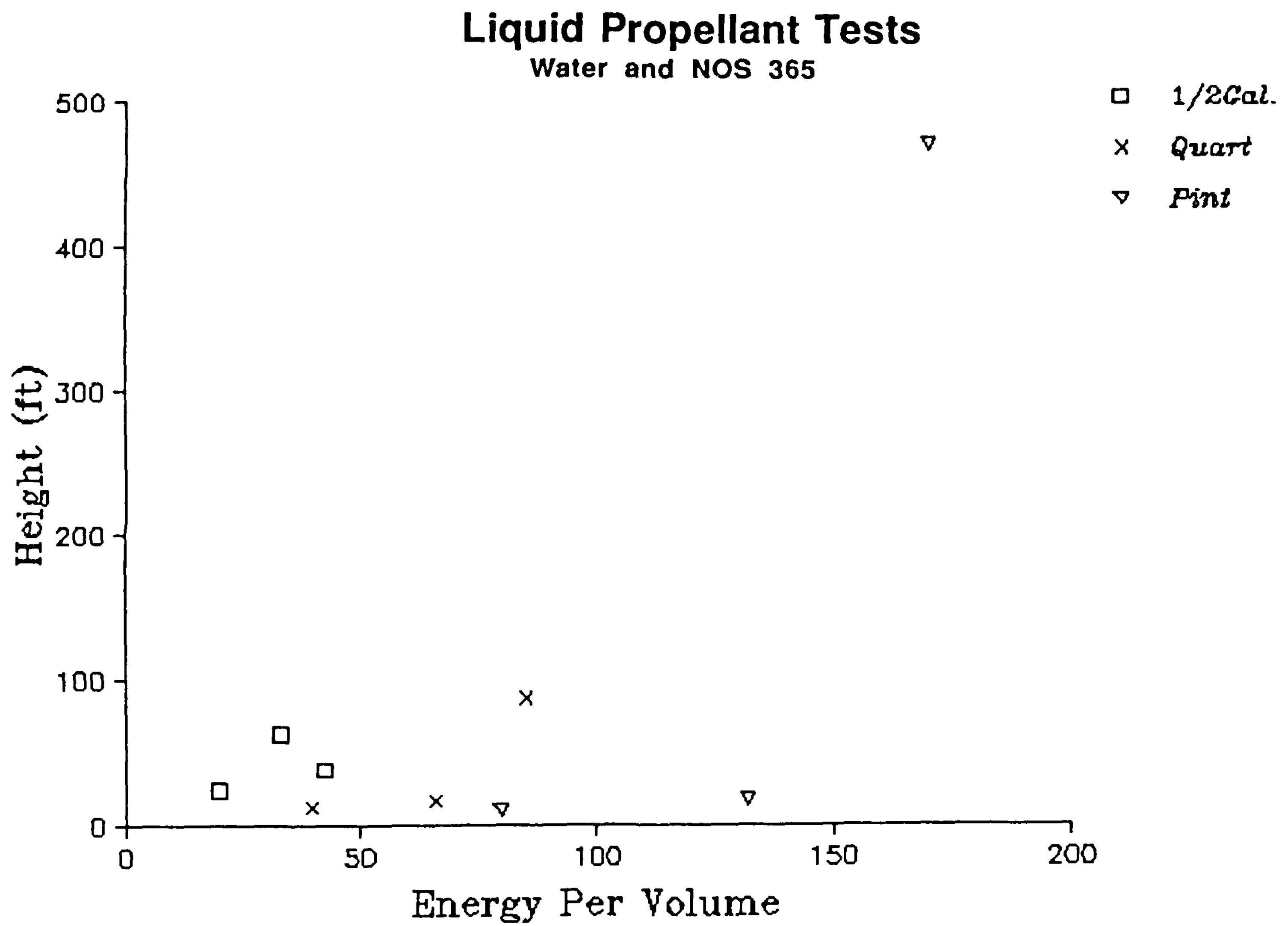


Figure 30. Witness plate height versus energy per unit volume

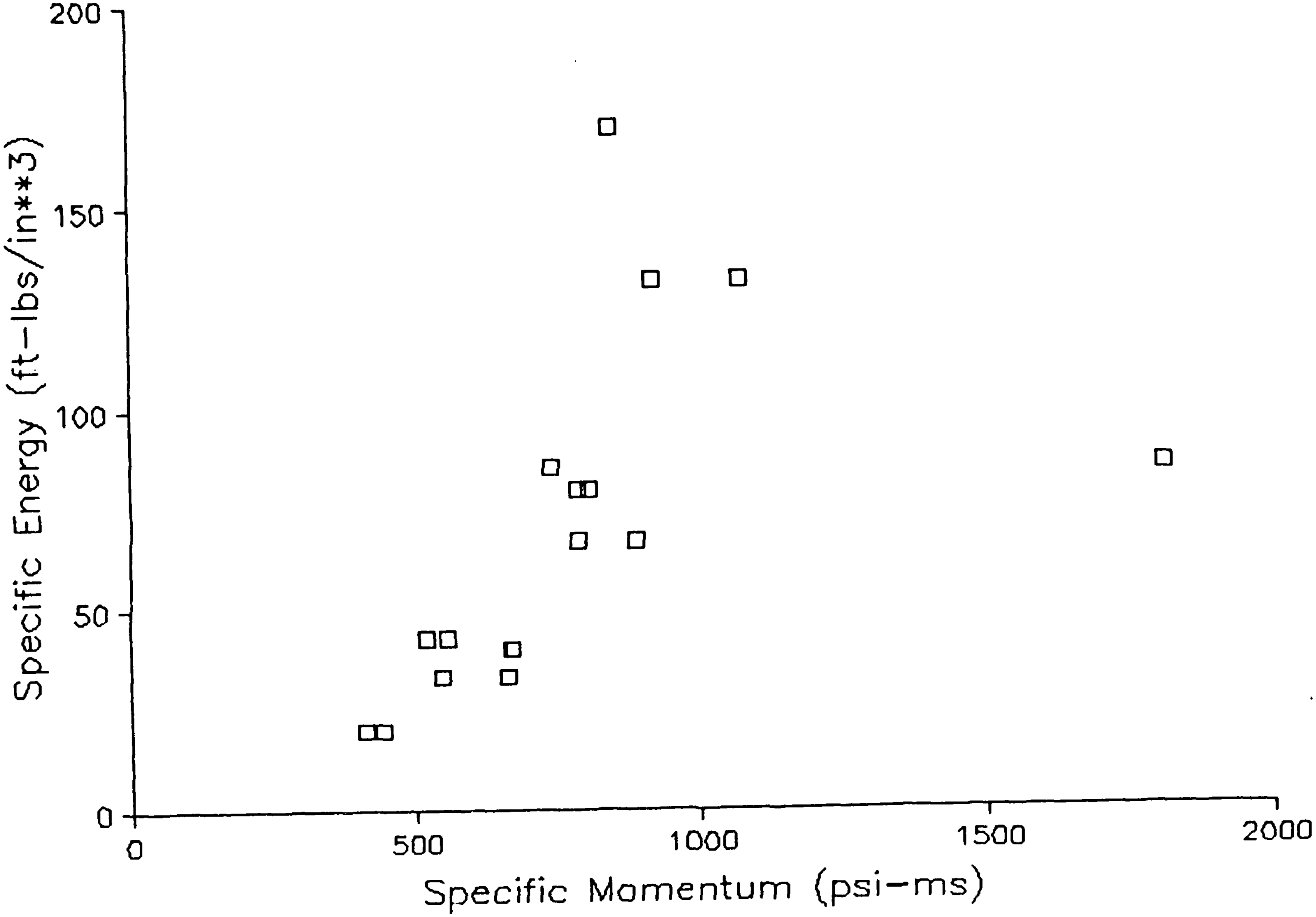


Figure 31. Witness plate momentum versus energy input

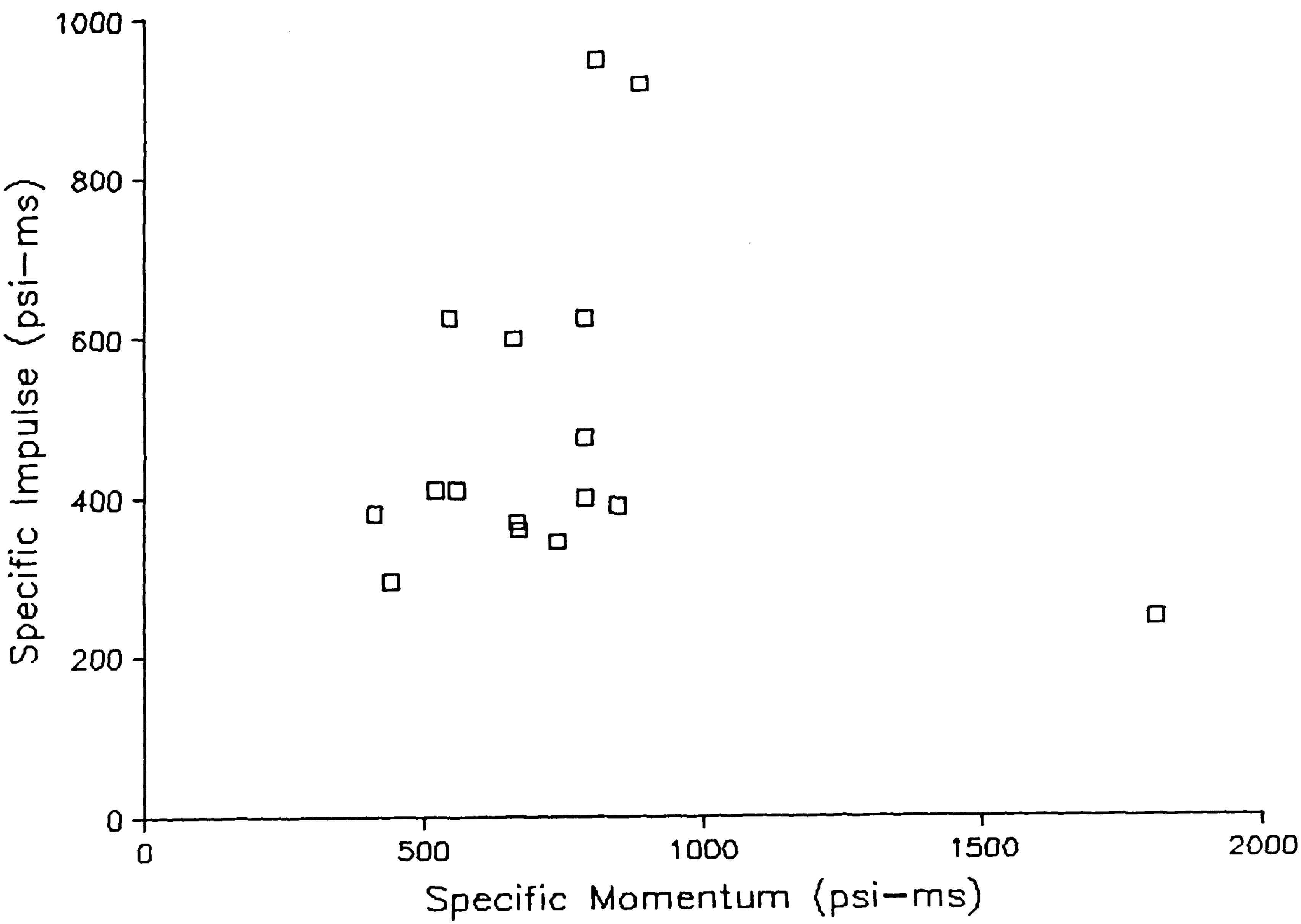


Figure 32. Witness plate momentum versus container impulse

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U.S. Army TRADOC Systems Analysis Activity
ATTN: ATAA-SL
White Sands Missile Range, NM 88002

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U.S. Army Infantry School
ATTN: ATSH-CD-CSO-OR
Fort Benning, GA 31905

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U.S. Army Field Artillery School
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ATSF-TSM-CN
Ft. Sill, OK 73503-5600

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U.S. Army Armor Center
ATTN: ATSB-CD-MLD
Ft. Knox, KY 40121

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U.S. Army Development and Employment Agency
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Naval Surface Weapons Center
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Code G33, J. East
Dahlgreen, VA 22448-5000

Commander
U.S. Naval Surface Weapons Center
ATTN: O. Dengel
K. Thorsted
Silver Spring, MD 20902-5000

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Naval Weapons Center
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Naval Ordnance Station
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Code 5251
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Naval Postgraduate School
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Kirtland AFB, NM 87117

Air Force Armament Laboratory
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ATTN: L. Caveny, B-410
Bolling AFB, FL 32542-5000

U.S. Bureau of Mines
ATTN: R.A. Watson
4800 Forbes Street
Pittsburgh, PA 15213

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Jet Propulsion Laboratory
ATTN: Technical Library
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Director
National Aeronautics and Space Administration
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MS-86, Dr. Povinelli
21000 Brookpark Road
Lewis Research Center
Cleveland, OH 44135

Director
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, TX 77058

Central Intelligence Agency
Office of Centeral Reference
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Washington, DC 20502

Central Intelligence Agency
ATTN: Joseph E. Backofen
HQ Room 5F22
Washington, DC 20505

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I. Magoon
J. Scudiere
100 Plastics Avenue
Pittsfield, MA 01201-3698

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Armament Systems Department
ATTN: D. Maher
Burlington, VT 05401

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ATTN: D. Gavin
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Dr. R. L. Dotson
P.O. Box 30-9644
New Haven, CT 06536

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P.O. Box 214
Elkton, MD 21921-0241

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ATTN: P. Gough
P.O. Box 1614
Portsmouth, NH 03801

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5240 Pearl Street
Rosemont, IL 60018

Science Applications, Inc.
ATTN: R. Edelman
23146 Cumorah Crest
Woodland Hills, CA 91364

Sunstrand Aviation Operations
ATTN: Dr. O. Briles
P.O. Box 7002
Rockford, IL 6'125

Veritay Technology, Inc.
ATTN: E.B. Fisher
4845 Millersport Highway
P.O. Box 305
East Amherst, NY 14051-0305

Director
Applied Physics Laboratory
The Johns Hopkins University
Johns Hopkins Road
Laurel, MD 20707

Director
Chemical Propulsion Information Agency
The Johns Hopkins University
ATTN: T. Christian
Technical Library
Johns Hopkins Road
Laurel, MD 20707

University of Delaware
Department of Chemistry
ATTN: Mr. J. Cronin
Professor T. Brill
Newark, DE 19711

University of Illinois at Chicago
ATTN: Professor S. Murad
Department of Chemical Engineering
Box 4348
Chicago, IL 60680

University of Maryland at College Park
ATTN: Professor F. Kasler
Department of Chemistry
College Park, MD 20742

University of Missouri at Columbia
ATTN: Professor R. Thompson
Department of Chemistry
Columbia, MO 65211

University of Michigan
ATTN: Professor G.M. Faeth
Department of Aerospace Engineering
Ann Arbor, MI 48109-3796

University of Missouri at Kansas City
Department of Physics
ATTN: Professor R.D. Murphy
1110 East 48th Street
Kansas City, MO 64110-2499

Pennsylvania State University
Department of Mechnical Engineering
ATTN: K. Kujo
University Park, PA 16802

Princeton Combustion Research Laboratories, Inc.
ATTN: N.A. Messina
M. Summerfield
475 U.S. Highway One North
Monmouth Junction, NJ 08852

University of Arkansas
Department of Chemical Engineering
ATTN: J. Havens
227 Engineering Building
Fayetteville. AR 72701

Director
U.S. Army Materiel Systems Analysis Activity
ATTN: AMXSY-D
AMXSY-MP, H. Cohen
Aberdeen Proving Ground, MD 21010-5066

Commander
U.S. Army Test and Evaluation Command
ATTN: AMSTE-TO-F
Aberdeen Proving Ground, MD 21005-5066

Commander
Chemical Research, Development and Engineering Center
ATTN: SMCCR-RSP-A
SMCCR-MU
SMCCR-MSI
Aberdeen Proving Ground, MD 21010-5423

Ballistic Research Laboratory
ATTN: SLCBR-IB-B, C. Leveritt
J. Knapton
W.F. Morrison
AMXBR-OD-ST
Aberdeen Proving Ground, MD 21005-5066